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The Development of Lineation in Complex Fold Systems

By P. CLIFFORD, M. J. FLEUTY, J. G. RAMSAY, J. SUTTON, and J. WATSON

ABSTRACT

The paper refers to a number of areas in which the lineations are related to major folds. It shows that the shapes of individual folds, the interference of neighbouring folds, and the imposition of a second generation of folds all influence the arrangement of linear structures and that lineation maps may only become explicable when the major structure has been determined.

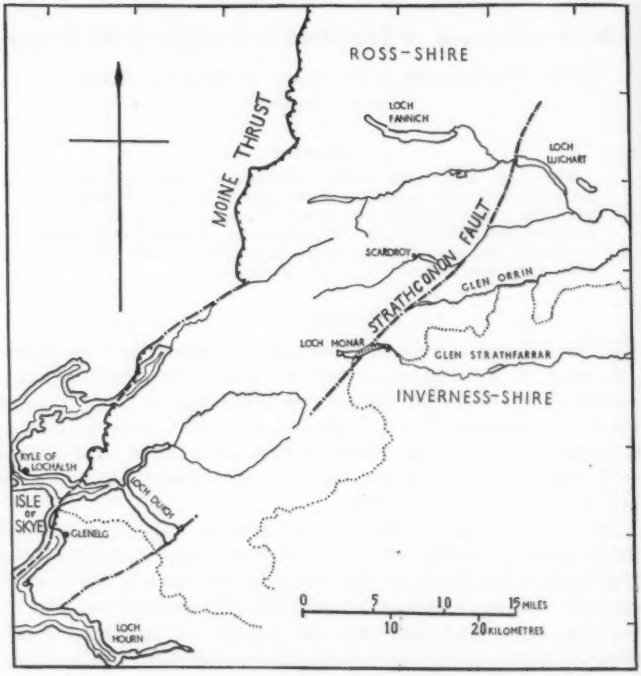
INTRODUCTION

THE existence of a simple geometrical relationship between certain types of linear structure and the folds with which they are associated is well known. Where such a relationship holds, maps of the linear structures show a simple pattern if the fold system itself is a simple one; but if the folding is more complicated, or if folding took place in several phases, then the pattern of linear structures may become extremely complex.

During the last seven years we have severally or jointly completed the mapping of a large area of metamorphic rocks in the Northern Highlands of Scotland. In the course of this work it has become apparent that the complexity of the folding varies from one part of the area to another, and that the patterns of associated linear structures show corresponding variations in complexity. Linear trends are rarely very constant and many of our lineation maps would have been quite unintelligible without a detailed knowledge of the major structures. Yet it has also become clear that the orientation of the linear structures is, just the same, governed by a very simple and well-known principle—these structures are, with a few exceptions, parallel to the axes of the folds to which they are related, and are developed parallel to the intersections of pre-existing foliation surfaces with the axial plane foliation.

We therefore have come to consider that the complications of linear trend with which we are dealing should be attributed to variations in the shape, arrangement, and mutual relationships of the large folds.

Our object in this paper is to illustrate, by reference to ground which one or other of us has mapped, some of the ways in which variations in complex fold systems may influence the pattern of linear structures related to the folding and to show that it is premature to discuss the significance of the linear structures (or of the microfabric) until one has established the nature of the associated folds.



TEXT-FIG. 1.—Sketch-map showing localities mentioned in the text.

Most of our examples are taken from an area about 300 square miles in extent which covers the entire width of the Moine outcrop near the Kyle of Lochalsh railway in Central Ross-shire and continues south-westwards to Glen Orrin and Glen Strathfarrar on the Ross-shire–Inverness-shire border (Text-fig. 1). Further illustrations come from the region of Glenelg, 24 miles south-west of Loch Monar; reference is also made to Dalradian rocks, near Portsoy, in Banffshire. Structural accounts of parts of these areas have appeared or are now in the press; other regions will, we hope, be described in due course.

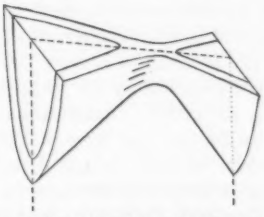
Local detail is kept to a minimum in this paper, but a detailed geological map of every area mentioned has been made by one or other of us.

The Geological Setting

The Central Ross-shire and Glenelg regions are made up largely of metamorphosed sediments of the Moine Series. Pre-Moinian Lewisian rocks, including highly altered sediments and a variety of gneisses, cover considerable areas at Glenelg. In Central Ross-shire, belts of hornblendic and acid gneisses, associated with a wide range of metamorphosed sediments, form bands in the Moine Series. Their stratigraphical position need not be debated here, since they behave geometrically in the same way as the Moinian strata alongside them.

The Fold Systems

In the most general terms, it may be said that the principal folds



TEXT-FIG. 2.—The form of a fold with variable plunge, developed about a constant axial plane.

in the Moinian area with which we are dealing (Text-fig. 1) have axial planes dipping in easterly, south-easterly, or southerly directions. There are many exceptions to this statement, resulting both from original variations in complex fold systems and from refolding by later structures. The plunges of the fold axes are, for the same reasons, also very variable, but plunges in south-westerly, southerly, or south-easterly directions predominate. The axial planes have in general been found to be more constant in orientation than the fold axes; for example, it is sometimes convenient to refer to a N.E.–S.W. fold system where the axial planes have this strike, even though the fold axis itself may plunge in any direction within the axial plane (cf. Text-fig. 2).

In Fannich Forest (Text-fig. 1) the major folds are open structures running north and south; they are associated with oblique or cross-folds. Further south the major folds are tighter, more complex, and belong to more than one fold system. The early structures have

been refolded about new axes. All the folding may perhaps be of Caledonian age.

The Linear Structures

The commonest forms of linear structures are striations produced by the intersection of bedding-plane foliation with an axial plane foliation which may be visible in the field or may be only incipient, when it is often revealed by fabric studies. Other types of lineation are produced by the parallel orientation of minerals, or of mullions, rods, augen, etc., and by the axes of small folds. Observations over a wide area suggest that in this part of the Moine Series all the types of lineation mentioned above have the same geometrical significance; the lineations lie in planes parallel to the axial planes of the folds to which they are related, and are parallel to the intersections of these planes with the bedding. However, the regular arrangement of the lineation can be modified by plastic deformation and sliding during the folding; this has happened at Glenelg.

It is generally easy to demonstrate in the field the close relationship between linear structures, axial plane schistosity, and small folds in the Moine Series. The connection between these structures and the major folds has been established by the mapping and by analysis of data on stereographic projections. Some evidence on these lines has already been published (Sutton and Watson, 1952, 1954) and more is now becoming available. In areas such as Fannich Forest, where the folds all appear to be roughly contemporaneous, only one generation of linear structures has been detected; near Loch Luichart, Glen Orrin, Glen Strathfarrar, and Glenelg, where multiple fold systems have been mapped, two or more generations of linear structures have been found.

The axis of a quartz microfabric girdle may be regarded as a special kind of linear structure. Some seventy fabric diagrams, mostly of quartz, have been prepared from specimens taken from the Moinian areas we have mapped. Wherever a girdle fabric has been found, the axis of the girdle lies parallel to the visible lineation, as Phillips (1937) first showed to be the rule in the Moines. Partial or complete crossed girdles have been found in regions of multiple fold systems (M. J. F., J. G. R.). It follows that the formation of the microfabric in the Moines is related to the development of the major folds, and this fact must be taken into account in considering the significance of the fabric.

In the following pages we illustrate, by means of specific examples, the strict relationship between the small structures and the largest mappable folds. We describe first some individual folds, and then associations of folds all formed during a single period of folding.

We then pass on to examples of the effects produced by the superposition of several generations of folds. In conclusion, we consider instances where sliding during folding has modified the arrangement of the linear structures.

Lineations Associated with Single Fold Systems

Lineations Associated with Simple Cylindrical Folds

The lineations associated with a cylindrical fold (whose surface can be generated by a line moving parallel to the axis) should, as is well known, all be parallel to one another.

This condition can be illustrated on a small scale almost everywhere within the areas with which we are concerned. Many folds exposed in single outcrops show on their limbs a lineation which is constant in direction. Folds of this type in the Moine Series have long been described (see figures in Wilson (1953), McIntyre (1950), Sutton and Watson (1954)). They appear to be the crenulate folds of Anderson (1948, with references to early work). Larger folds approximating to the cylindrical type have been mapped by us in some areas—for example, in the region of Loch Monar—but as a rule, the profiles of the major folds change rather rapidly in the axial direction and the folds therefore cease to be of cylindrical type.

Lineations Associated with Folds of Conical Type

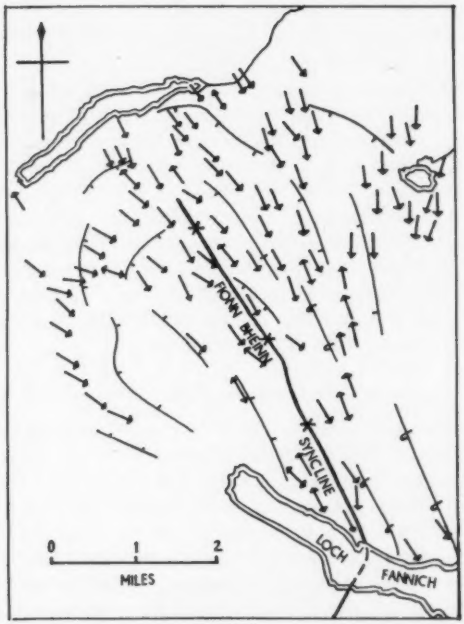
Where changes of profile result in the opening out and dying away of a tight major fold, the structure ceases to be cylindrical and approximates more nearly to a conical fold (Stockwell, 1950); where this kind of structure exists, the lineations have been found to show a fan-shaped arrangement converging on the vertex of the fold.

The Fionn Bheinn syncline (Sutton and Watson, 1954) is a south-easterly trending structure which has been traced for a distance of 20 miles in the western part of the Moine outcrop. It is almost isoclinal over much of its course, but north of Loch Fannich it opens out into a gentle fold which dies away some 3½ miles north of the loch. In this northern region (Text-fig. 3) the plunge varies from zero to 7 degrees south-east. The linear structures along the hinge line are parallel to the axis of the major fold; those on the fold limbs converge on the tightly-folded southern part of the syncline. Thus, lineations two miles west of the hinge line trend 60 degrees east of south, whereas the linear structures between 1½ and 2½ miles east of the hinge run practically north and south, the intervening structures swinging round from one position to the other. Axial plane foliations (in Fairbairn's sense, 1949, p. 5) are sparsely developed in the region shown in Text-fig. 3, but their strikes also tend to converge on the

vertex of the fold. The linear structures lie at the intersection of bedding with the axial plane foliation, where this is developed; and their fan-like arrangement is thus clearly bound up with the shape of the major fold.

Folds of Varying Trend and Plunge, or Inconstant Folds

In the region of Loch Fannich (Sutton and Watson, 1954), the fold

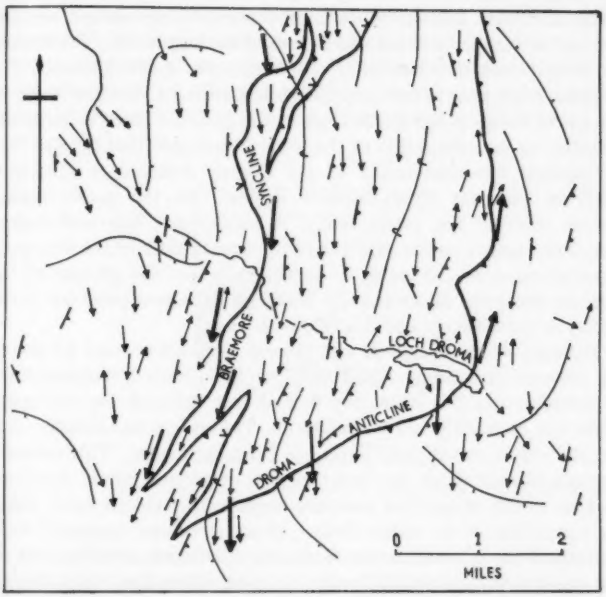


TEXT-FIG. 3.—Map of the northern end of the Fionn Bheinn syncline (thick solid line shows fold trace). Thin lines, generalized strike lines. Arrows, axes of minor folds and associated lineations. (J. S., J. W.)

pattern is characterized by three features: the orientation of both the axis and axial plane of each fold is variable; the attitudes of neighbouring folds vary in different ways; and these fluctuations appear to be original features of the fold system. These folds, which we suggest might be called *inconstant folds*, each developed about a curved axial plane, the curvature differing from that of the axial planes of adjacent folds. It is not possible to form a fold having a curved axial plane without producing subsidiary wrinkles, and in

fact the major folds of the Fannich system are accompanied by subsidiary folds situated opposite the most pronounced inflections of the major structures.

The linear structures associated with the inconstant folds fall into two groups—those which run parallel to the major fold axes and which follow more or less faithfully their changes in trend and



TEXT-FIG. 4.—Map of the Braemore syncline and Droma anticline, Fannich Forest (dip of axial plane shown by arrow-heads along trace). Long thin lines, generalized strike lines; short lines, axial planes of minor folds and axial plane foliation. Large arrows show plunge of major folds; small arrows, plunge of minor folds and lineations. (J. S., J. W.)

plunge, and those which are parallel to the subsidiary folds. Some of the resultant complications can be illustrated by the lineation pattern of the region north-east of Loch Fannich (Text-fig. 4).

In this region there are two major folds with axial planes dipping eastward—the Braemore syncline in the west and the Droma anticline in the east (Sutton and Watson, 1954). Both axial planes are arched, producing mild antiforms plunging eastward. Near Loch Droma, the axial plane of the Droma anticline lies about 2½ miles from the

Braemore syncline and strikes north–south. South of the loch it bends round south-westward and approaches the Braemore syncline; the two structures join and come to an end in the south of the ground shown in the figure. A similar though less rapid convergence narrows the distance between the two axial planes north of Loch Droma.

The cleavage, and the axial planes of small folds, run parallel to the axial planes of the nearby major folds and in consequence the linear structures formed by the intersection of cleavage and bedding follow the changes in trend and plunge of the large folds. The Droma anticline shows a culmination of plunge near Loch Droma. The Braemore syncline everywhere plunges southward, but the angle of plunge is lower in the north than in the south. These changes are reflected by the orientation of the linear structures (Text-fig. 4).

Opposite the culmination of the Droma anticline, a subsidiary antiform plunging south-eastward appears on the gently-dipping eastern limb of the major fold. A similar but less well-marked structure appears on the gently-dipping western limb of the Braemore syncline opposite the point of inflection where the plunge of the syncline steepens. South-easterly lineations have been observed in the region of these two cross-folds (Text-fig. 4).

The axes of the Braemore and Droma folds are crossed by one of the traverse lines along which Phillips (1937) recorded observations of lineation and it is interesting to find that although the two major folds run essentially north and south, Phillips' reconnaissance map records only south-easterly lineations from the region. This anomaly appears to arise from the fact that well-developed minor structures parallel to the major fold axes are largely restricted to zones along the hinge-lines of the major folds. Minor structures associated with the subsidiary cross-folds are frequently developed on the limbs of the major structures and in Fannich Forest, where the gently-dipping limbs have very broad outcrops, random observations are likely to record only lineations associated with the subsidiary structures.

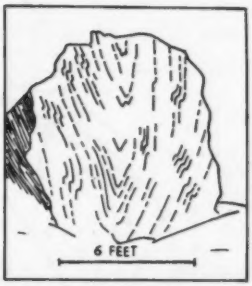
It is clear from Text-fig. 4 that although the lineation pattern is complex, it is very closely related to the fold pattern. All the various lineation directions run parallel to the axes of large folds which are, according to our evidence, the principal structures of the district.

Folds Refolded About Their Original Axes

The formation of involutions, due to the continuation of folding on the original axial directions after the first-formed structures had become more or less isoclinal, is to be seen on a small scale in several localities. The same process, acting on a larger scale, has led in some places (for example, in the ground south of the eastern end of Loch Fannich) to the flexing of the axial plane of a major fold,

and in others (for example, south-west of Loch Monar) to a dispersion of the strikes of minor axial plane structures. Since the refolding takes place about the original axes, the lineation-patterns may remain quite simple and may, therefore, be inadequate as guides to the major structures.

In the region between Loch Duich and Loch Hourn, near Glenelg, the tract of siliceous Moinian rocks which lies two to three miles east of the Sound of Sleat provides many examples of small, often isoclinal, folds which have been refolded about the original axial direction (J. G. R., J. S., and J. W.). They are related to three major folds—the Beinn a' Chapuill antiform, the Gleann Beag synform south of Glenelg (J. G. R.), and the Letterfearn antiform near Loch Duich (J. S., J. W.)



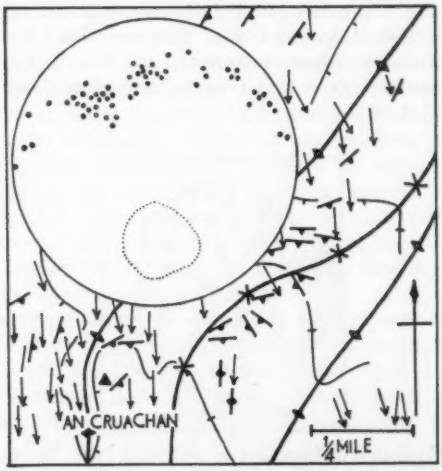
TEXT-FIG. 5.—Isoclinal fold refolded by later small folds. North of Beinn a' Chuirn, three miles east-north-east of Glenelg. (J. S.)

One of the minor folds on the western limb of the Letterfearn antiform is shown in Text-fig. 5. This structure is a moderately tight fold which is crossed by a number of much smaller wrinkles. The wrinkles fold the axial plane of the larger structure and are therefore somewhat later than it; but their axes are parallel to the axis of the larger fold and we regard them as belonging essentially to the same phase of folding.

The foliation surfaces of the folded rocks shown in Text-fig. 5 exhibit a single set of lineations which are parallel to the axes of both generations of folds. So far as the arrangement of the lineations is concerned there is no difference between these rocks and rocks of such regions as Fannich Forest which have a simpler type of structure without any obvious refolding.

An example of refolding about original axes on a somewhat larger scale is provided by the structures mapped by one of the writers (J. G. R.) in the region of An Cruachan, a hill 3½ miles south-west of

the west end of Loch Monar. Here (Text-fig. 6) a system of folds on N.E.–S.W. axial planes, with southerly plunges, has been recognized (Ramsay, 1954). North of An Cruachan the axial planes of related small folds, and the cleavage, dip steadily south-east at angles of 40 to 50 degrees, but on the hill itself the axial planes and cleavages show marked variations in strike. A stereographic plot of the poles of these structures (inset of Text-fig. 6) shows that they are not



TEXT-FIG. 6.—Sketch-map of major and minor folds at An Cruachan. Thick line with diamond ornament, axial trace of major antiform; with cross ornament, axial trace of synform. Thin lines, generalized strike lines. Short lines, axial planes of minor folds and axial plane foliation. Arrows; axes of minor folds. Inset: stereographic projection of poles to axial planes of minor folds and to axial plane foliation (dots) and field in which linear structures fall (marked by dotted line). (J. G. R.)

haphazardly arranged, but are dispersed about an axis parallel to that of the original small folds and major structures.

The ground north of An Cruachan is made up of regionally-metamorphosed siliceous granulites, but near the summit a variety of migmatized rocks appear. The periods of folding and migmatization appear to have overlapped (Ramsay, 1954) and it seems probable that the change in structural style as one goes southward on to An Cruachan is connected with the uneven migmatization.

The lineations show a consistent southerly plunge, both in the relatively simple region to the north and in the permeated ground

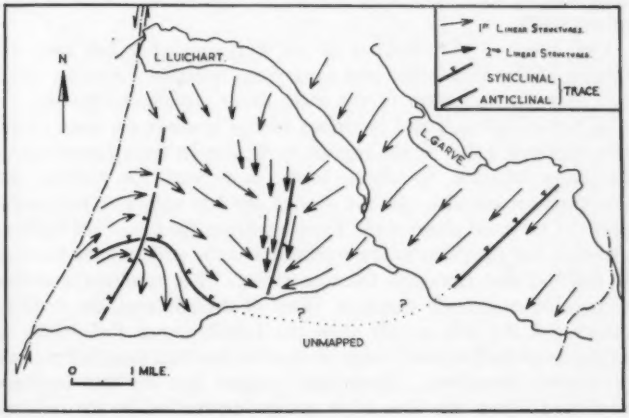
where refolding of the original structures has taken place. The pattern of the linear structures, therefore, does not reveal the complications of the tectonics.

Linear Structures Associated with Multiple Fold Systems

We now turn to the more complicated arrangements produced when rocks have been refolded about differently oriented axes. The evidence we have seen indicates that not only are the linear structures associated with the earlier generation of folds deformed by later phases of movement, but the linear structures belonging to the later series of folds are themselves influenced by the pattern of the earlier folds. We will consider these two phenomena separately.

Linear Structures Associated with the Early Folds of Multiple Fold Systems

The effect of refolding on an earlier lineation-pattern changes



Text-fig. 7.—Sketch-map of part of Tarvie syncline, Loch Luichart. (P. C.)

considerably from districts where the later folds are comparatively open to those where they are tight and complex. The region south and east of Loch Luichart, and part of the Loch Monar region, respectively, illustrate these two conditions.

Near Loch Luichart, one of us (P. C.) has recognized a fold several miles long which has been given the name of the Tarvie syncline. The northern fold limb and the axial plane of the fold have a strong curvature in the region covered by Text-fig. 7; the southern limb, which is inverted, is not considered here. The minor linear structures

are congruent with the fold. In the east of the area, both the Tarvie syncline and the linear structures plunge to the south-west, but near the centre of the ground is a zone marked by southerly-plunging lineations and small folds, many of which refold small structures that run parallel to the Tarvie syncline. West of this zone, the syncline and the associated linear structures plunge to the south-east. In the extreme west, the syncline makes another bend, beyond which the outcrop of the axial plane once more runs south-west, though the lineations still plunge generally eastward.

The explanation of these facts seems to be that the Tarvie syncline has been folded by two later folds running from north to south. Both these later folds plunge steeply south and have almost vertical axial planes. The large late antiform in the east is accompanied by a narrow belt of congruent minor folds. Since they cut the foliation trend almost at right angles, all these late folds are symmetrical in profile. This style may be contrasted with the elongate isoclinal cross-section characteristic of the Tarvie syncline and its associated minor folds.

One effect of the refolding of the Tarvie syncline has been the folding of the axial plane and axial plane foliation. Another effect has been the deflection of the early linear structures (Text-fig. 7). The Tarvie fold axis and lineations plunge towards the trace of the late antiform, a fact which appears to be due to the arrangement of the early foliation, to whose intersections with the bedding the lineations are parallel. To the west of the late antiform, and to the north of the axial plane of the Tarvie syncline, the dip of the bedding planes is less than that of the foliation and the strike of the bedding is anticlockwise from the foliation strike. The resultant lineation plunges in an easterly direction. East of the antiform, the bedding planes still dip less steeply than the foliation, but their strike is clockwise of the foliation planes, so that the resultant lineation plunges in westerly directions. These facts suggest that the late antiform developed along the line of a plunge depression in the original synform. Such a plunge depression may be inferred from mapped turn-overs at either end of the Tarvie syncline.

The Loch Monar district, recently described by one of us (Ramsay, 1954), serves to illustrate the effects of refolding more intense than that affecting the Tarvie syncline. The Loch Monar synform, belonging to an early series of east–west folds, is crossed by a later series of S.W.–N.E. folds which have deformed and, in some parts of the ground, obliterated the earlier structures.

The Loch Monar synform runs roughly east and west; its southern limb is steep and inverted and its northern limb dips more gently south-westward. At the eastern end of the synform (Text-fig. 8), the

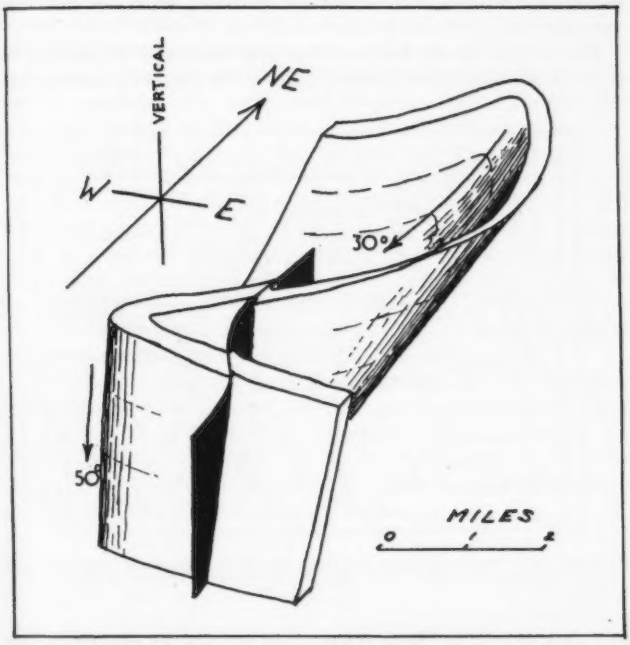
TEXT-FIG. 8.—Map of Loch Monar synform near the east end of Loch Monar. The axial trace of the L.M. Synform is shown to be refolded by later antiforms and synforms (thick lines with arrowheads indicating dips of limbs). Arrows with ornamented tails, minor fold axes and lineations associated with the L.M. Synform. Plain arrows, minor folds and lineations associated with the later folds. (J. G. R.)

effects of later folding are less pronounced than they are further west, and the axial zone is easily recognizable on Beinn na Muice, the mountain two miles east of the east end of Loch Monar. Near the fold hinge, well-developed lineations plunge westward parallel to the fold axis and to the intersection of axial plane foliation with bedding-plane foliation. On the limbs of the synform, however, the prevailing lineations run south-westward and lie in foliation planes which are oblique both to the bedding and to the axial plane of the Loch Monar synform. These foliation planes are parallel to the south-easterly-dipping axial planes of later folds which cross the synform. Rocks on the limbs of the synform are refolded by these late structures, and stereographic plots of the poles of bedding planes reveal girdles about south-westerly axes. The hinge-line of the Loch Monar synform appears to be less affected by refolding, and here the early lineations are preserved.

West of the river draining Loch Monar, the hinge-line can no longer be traced with certainty, owing to the effects of refolding. However, a belt containing westerly-plunging small folds and lineations can be traced westward from the axial zone east of the river, and it seems probable that this belt represents the hinge-line, where the early structures were preserved. About three-quarters of a mile west of the river, the supposed hinge-line swings round the axis of a large late antiform (Text-fig. 8). West of this antiformal axis, the early lineations plunge northward at angles of about 70 degrees. Further west still, the supposed axial zone, again represented by the zone of early lineations, is bent back into a westerly course by another late fold. Beyond this fold, the early lineations plunge eastward.

Minor structures associated with the Loch Monar synform are preserved chiefly along the hinge-line. The effect of refolding on their orientation is brought out by Text-fig. 8. Outside the axial zone, south-westerly lineations related to later folds are the rule. The axial zone is narrow, and it is clear that if it were poorly-exposed, a lineation-map would show up only the later south-westerly structures and would provide no evidence of the existence of earlier folds such as the Loch Monar synform. Other lines of evidence, however, show up the existence of two generations of folds. It can be demonstrated by mapping, and the two sets of minor structures are distinct in style as well as in orientation. Moreover, the later structures are themselves influenced by the form of the early folds. Geometrical considerations suggest that where late folds are superimposed on a structure like the Loch Monar synform, the direction and angle of plunge of the second fold axes must be dependent upon the dip of the first fold limbs. This is borne out by the observed facts; where the more

gently-dipping northern limb of the Loch Monar synform is refolded, the second folds and their associated lineations plunge gently to the south-west; where the steep inverted limb of the synform is refolded, the second folds and their lineations plunge vertically, or very steeply to the south. In the field, a line along which there is a marked change in plunge, and in profile, of the later structures can be mapped, and



TEXT-FIG. 9.—Block diagram of the Glen Orrin Synform and Sgurr na Fearstaig fold (the plunge of the latter is *ca.* 50 towards the observer). Probable tectonic thinning of the common limb shown. One of the small-scale later folds is indicated diagrammatically with its cross-cutting axial plane shown in solid black. (M. J. F.)

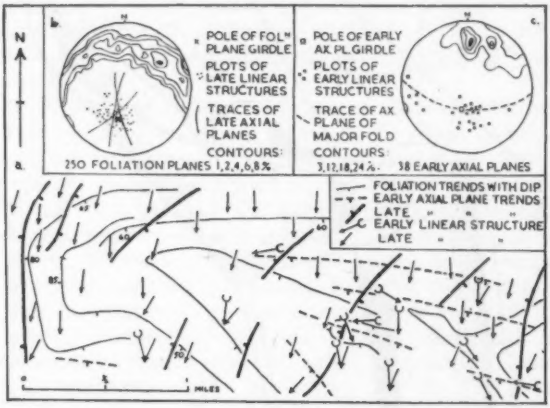
this line coincides with the trace of the synform established on the evidence given above.

A final example of the effect of refolding on early structures may be taken from the high ground between Glen Strathfarrar and Glen Orrin where intense distortion appears to have accompanied the later folding (M. J. F.). Here, the Sgurr na Fearstaig fold (Text-fig. 9) is an early structure separating the Loch Monar synform to the south from the similar Glen Orrin synform to the north. The

fold cannot be described as an antiform, for it closes not upwards but sideways and its axis plunges down the dip of the axial plane.

The axial trace of the Sgurr na Fearstaig fold strikes just south of east (Text-fig. 10). Both limbs dip southward, the northern limb at 50 to 60 degrees and the southern limb at 45 to 55 degrees. In the east, the two limbs converge on a sharp hinge, but in the west the turn-over is broader, and the beds on the blunt " nose " are practically vertical.

The attitude of the fold axis has been calculated by plotting the poles of foliation planes from all parts of the fold on a stereographic



TEXT-FIG. 10.—Structural map and diagrams of the Sgurr na Fearstaig fold. (M. J. F.)

net; they fall on a girdle whose axis plunges 53 degrees to 193 (Text-fig. 10*b*). Tight minor folds associated with the major structure have axes and axial planes of rather variable orientation (Text-fig. 10*c*). Their axial plane poles form a partial girdle practically identical with that of the foliation planes. This partial girdle, however, shows a maximum which may represent the pole of the axial plane of the major fold; this plane strikes 094 and dips 58 degrees south.

Small folds of a more open style, which are incongruent with respect to the major structure, are also present and occasionally can be found to warp the tight congruent folds. The axial planes of these folds vary with their position on the major fold (Text-fig. 10*a*). The late fold axes and related lineations show an appreciable scatter (Text-fig. 10*b*), and their orientation differs slightly on the two limbs

of the early fold, but they are invariably parallel to the intersections with the bedding foliation of the late axial planes (Text-fig. 10*b*).

Study of Text-fig. 10*b* shows that the late lineations fall round the pole of the foliation plane girdle, i.e. the axes of the early major fold and the late minor folds are parallel. Yet the late lineations are related to axial plane foliations which cut across the major structure, and there can be no doubt on the local and regional evidence that the two sets of structures belong to different phases of folding.

Early lineations are preserved near the core of the major fold (Text-fig. 10*a* and *c*) and their distribution helps to resolve this apparent anomaly. The early linear structures show a considerable scatter, but lie more or less within the axial plane of the major fold. This fact suggests that the present southerly plunge of the Sgurr na Fearstaig fold does not represent the original attitude of its axis, which may once have shown a gentle plunge comparable with that of the Loch Monar synform. If this is so, the parallelism of the axes of the early and late folds may be a result of distortion of the earlier fold by later movements. The nature of this distortion cannot be discussed here, but it does not seem to represent the simple type of refolding described in earlier pages and its effect on the orientation of early linear structures is correspondingly complex.

As at Loch Monar, one set of linear structures is overwhelmingly predominant and early linear structures are very uncommon. The two distinct sets of axial plane structures, however, show up the complications of the tectonic history; it seems imperative in areas such as this to record all types of structural data, since observations of linear structures alone may be misleading.

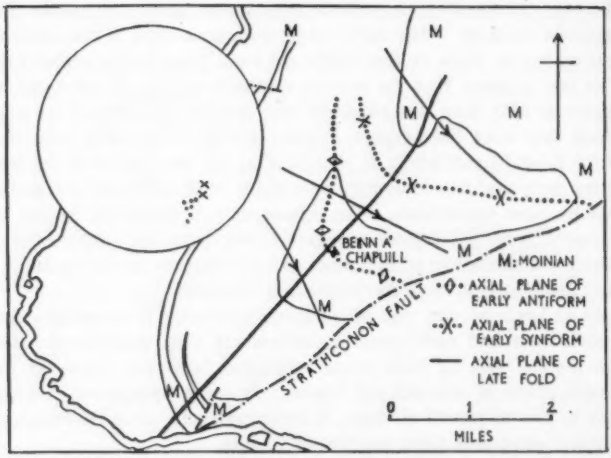
Linear Structures Associated with the Later Folds of Multiple Fold Systems

The influence of early structures on the attitude of later structures received passing mention in connection with the Loch Monar area; it can be well illustrated by reference to folding in the Beinn a' Chapuill region two to three miles south-east of Glenelg (J. G. R.).

In this region (Text-fig. 11) broad belts of Lewisian rocks alternate with rock of the Moine Series. On Beinn a' Chapuill and in nearby Gleann Beag, these rocks are bent by two large folds. The Beinn a' Chapuill fold has in the past been accepted as a syncline (Clough in Peach and others, 1910; see also Kennedy, 1955), but evidence obtained by Ramsay, which it is hoped to publish elsewhere, indicates that this fold is in fact an antiform, and that the Gleann Beag fold is a synform. Both the folds mentioned above are refolded by a later flexure with a N.E.–S.W. axial plane. The axial planes of the earlier

folds are bent by this flexure in the manner shown in Text-fig. 11 (cf. Clough in Peach and others, 1910, p. 6).

The axis of the late fold plunges to the south-east, down the dip of its axial plane. A swarm of minor linear structures related to this fold plunge in the same general direction, but there are rather constant differences in trend between the linear structures south-west of the axial plane of the Beinn a' Chapuill antiform and those in the region north-east of the axial plane. The lineations in fact tend to



TEXT-FIG. 11.—Map of folds in the Beinn a' Chapuill region, south of Glenelg. Arrows: axes of minor folds and of lineations associated with the late fold. Inset: stereographic projection showing concentrations of late lineations. Dots show lineations on north-east limb of early synform and on south-west limb of early antiform. Crosses show lineations on common limb of the two early folds. Note how the lineations diverge from the antiform and converge on the synform. (J. G. R.)

diverge south-eastwards from the hinge line of this early fold and to converge on the hinge line of the Gleann Beag synform, and it appears that the orientation of the limbs of the earlier folds controlled to some extent the attitude of the structures formed during the later movements.

The effects of this control can be seen by plotting separately on a stereogram the concentrations of late linear structures recorded from each limb of the Beinn a' Chapuill fold (see inset, Text-fig. 11). The structures are seen to fall in two clusters. The major axis of refolding of each limb of the Beinn a' Chapuill antiform can be

calculated by plotting on a stereogram the poles of bedding planes on each limb; it is found that the late linear structures developed on each early fold limb are grouped about the axis of refolding of that limb. An angle of about 15 degrees separates the two axes of refolding.

It is obvious that the intersections of the variously-oriented early fold limbs with the constantly oriented axial planes of the later generation cannot be everywhere parallel and the variations in the pattern of the later lineations are apparently due to this fact. It is especially noteworthy that the later lineations diverge from the axial trace of the Beinn a' Chapuill fold and converge on that of the Gleann Beag fold. This fact is in harmony with the interpretation of these two folds as an antiform and a synform respectively. Once again it appears that the lineation pattern is intelligible and significant when taken in conjunction with the folding.

Linear Structures Associated with Intensely Deformed Belts in Folded Rocks

The linear structures described hitherto run more or less parallel to the axes of the largest folds in the system to which they are related and lie consistently parallel to the intersections of bedding and axial plane foliation. We propose now to mention two regions where neither of these relationships is strictly maintained. The first region is made up of Dalradian rocks and the second of Lewisian rocks associated with the Moine Series near Glenelg.

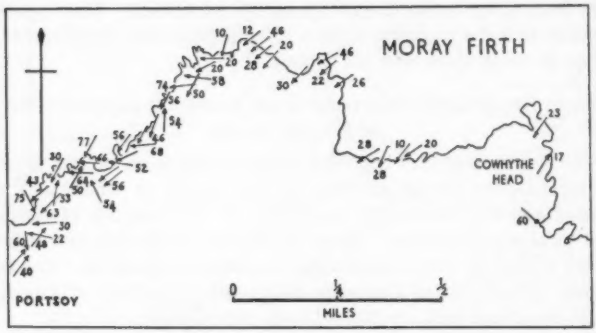
A very large asymmetrical syncline which two of us have named the Boyndie syncline (Sutton and Watson, 1956) appears along the Banffshire coast. The western limb of this structure includes a large part of the Dalradian succession and in the middle of it is developed a tectonic mélange some two miles thick. Part of this mélange is well-exposed near Portsoy where the linear structures with which we are now concerned are developed (Text-fig. 12).

The Boyndie syncline trends north-north-east and plunges in that direction at angles of less than 10 degrees. Outside the region of the tectonic mélange, congruent minor folds with similar trend and plunge are common. Near Portsoy, within the mélange, however, the linear structures plunge at high angles and in a variety of directions (Text-fig. 12).

The rocks involved include a variety of quartzites, siliceous granulites, limestones, and pelites and the degree of feldspathization is moderately high. The incompetent pelites (Sutton and Watson, 1956) are thrown into small puckers or into folds measurable in feet or tens of feet. Within this incompetent matrix lie boudins, mullions, torn-off fold hinges, rods, and spindles of the competent rock types.

The lineations produced by all these structures show comparable variations in plunge and they are not distinguished in Text-fig. 12.

The plunge of the linear structures in the tectonic mélange varies rapidly in a manner which cannot be explained by refolding, for neighbouring lineations developed in the same plane show marked and inconsistent variations within the plane. This pitch variation in a single plane can be as much as 90 degrees between two structures a few feet apart. The amount of variation, the contrast between the gentle plunge of the major fold and the steep plunges of minor structures near Portsoy, and the obvious connection between these structures and the development of the tectonic mélange all suggest



TEXT-FIG. 12.—Map showing attitude of linear structures in the tectonic mélange east of Portsoy, Banffshire. (J. S., J. W.)

that the linear structures here are connected with the intense deformation of a zone of rock within the limb of the major fold.

Somewhat similar structures appear to exist further south-west along the Dalradian outcrop (King and Rast, 1955). They usually seem to occur near a line separating two contrasting tectonic styles, and thus lie in parts of the crust where irregular movements might be expected. Structures of a comparable type have been found near Glenelg, where again they lie near the boundary of a zone showing a characteristic type of folding.

Between Loch Duich and Loch Hourn a well-developed rodding and lineation is associated with the older of the two fold systems referred to in an earlier section. These linear structures have locally been deformed during the later phase of folding; sliding and plastic movement appears to have taken place during the refolding, with the production of some remarkable structures noted first near Loch Hourn

(J. G. R.) and subsequently in regions north of Glenelg (J. S. and J. W.).

The effect of distortion during refolding is exhibited by some Lewisian rocks in the neighbourhood of Glas Eilean, on the north shore of Loch Hourn (J. G. R.). Here, sharp angular puckers, mostly of the order of a few inches to a few feet in amplitude, refold strongly lineated granulitic or schistose rocks. Theoretically, in a process of simple bending, or of folding by movement along the axial plane cleavage, the angle between the early lineation and the new fold axis should be the same on all parts of the new fold. In the region which we are now considering, however, the angle between the lineation and the axis of refolding is wide on the limbs of the new folds and narrows towards the hinges. The early lineation is thus twisted in a manner which seems to have involved considerable distortion during the later folding; it is impossible to "unfold" the early lineation on a stereographic net by rotating the new fold limbs back into a single plane. Distortion on a larger scale capable of being represented on a map appears to have accompanied the refolding of the region between Beinn a' Chapuill, Loch Hourn, and the Sound of Sleat.

A rather different phenomenon is illustrated by refolded Lewisian rocks exposed on the south shore of Loch Duich, at several localities about three-quarters of a mile south-east of Fern Villa (J. S., J. W.). At these localities, many of the rocks retain a strong lineation produced during the earlier period of folding, but have been sheared, granulated and locally refolded by the later movements. Even in outcrops where no late folds are visible it is apparent that the lineation has been very seriously disturbed. At one point just north of the Manse, erosion has cleaned the surfaces of a number of foliation planes; these planes are not refolded, but it can be seen that the lineation on them bends, sometimes through angles of up to 70 degrees, in the space of a few feet. Moreover, lineations on foliation planes only separated from each other by an inch or so of rock, often have noticeably different trends.

Distortion of an earlier lineation in the manner described above seems to represent a more complex condition than that of the refolded regions described in previous sections. The distortion is, however, connected with refolding, for it has only been found in localities where there is independent evidence of a second folding phase. It appears to us that this phase must have been accompanied by plastic deformation and by sliding along the foliation planes.

Discussion

The greater part of this paper has dealt with structures affecting the Moine Series and the Lewisian rocks associated with it, and since

so many recent discussions on the significance of lineation and petrofabric analysis have hinged on evidence from this series, it seems allowable to turn from our main topic to a brief consideration of Moinian structures.

The study of lineation in the Highlands goes back some seventy years to the time when the Geological Survey first broke ground in the north-west. Clough, in particular, was careful to record lineations, mullions, and the like, and so were a number of geologists who came under his influence. There is, however, no complete map of small-scale structures in the northern Highlands. This is a great pity for, in our experience, the pattern of lineations is often so complicated that nothing short of mapping on a scale of 6 inches to the mile is likely to elucidate it. Maps prepared from traverses tend to suggest illusory simplicity.

It is generally accepted that in the Moines the lineations are parallel to the axes of minor folds, and where the fabric has been investigated and a girdle fabric found, the axis of the girdle appears to be parallel to the lineation. There is, however, little agreement as to what, if any, relation these minor structural elements bear to the major tectonics. An excellent recent summary of the various suggestions is provided by the Regional Guide (Phemister, 1948) and the evolution of ideas is brought out by the discussions of papers read to the Geological Society (e.g. Phillips, 1937; Anderson, 1948; Kvale, 1953; Sutton and Watson, 1954). Many geologists have regarded the lineation as being related to the Moine Thrust movements. Phillips was the first to suggest that lineation and microfabric were related to a N.W.–S.E. system of folding accompanying the regional metamorphism, and that the metamorphism was associated with compression along north-east and south-west lines. A third view appears to deny any regular connection between the lineation and the large structures; a rather similar position is implicit in the suggestion that the quartz orientation revealed by petrofabric analysis might have been produced by stresses not revealed by the coarse structures of rocks seen in the field.

To a greater or less degree all these propositions consider the lineation to be something distinct from the largest folds in the Moines. Yet Richey (in Wilson, 1946) recorded that in the Morar anticline " the trace of the regionally developed cleavage appears as lineation upon the bedding planes of the mica-schists, and the lineation follows the B direction, and, in its inclination, the pitch of the fold ". In this paper we have mentioned fifteen folds, many of them several miles in amplitude, which are directly related to the linear structures. We have found no linear structures which are not related to some fold, though the relationship may not be apparent without detailed

mapping. The hypothesis put forward by Anderson (1948) that the lineation is parallel to the shearing movement is inconsistent with the facts observed in this ground.

Phillips' contention that the lineation and microfabric of the Moines as a whole developed during folding and regional metamorphism is supported by the evidence known to us. However, we dissent from Phillips' view that the regional folding of the Moines occurred about N.W.–S.E. axes. This deduction, based on observations in widely scattered localities, is in our opinion too great a step to take without the supporting evidence of structures on some intermediate scale mappable in the field. It now turns out that over a considerable area of the Moine outcrop there is to be found evidence in flat disagreement with this deduction—e.g. certain of the folds in Fannich Forest, the Tarvie Syncline, the Monar Synform, none of which plunge to the south-east.

The general conclusions which arise from the evidence described in this paper have for the most part been dealt with already. Except in ground such as the Portsoy region where sliding or distortion accompanied folding, there is a constant relationship between the small and the large structures, though this relationship is often obscured by the complexity of the folding. In particular, we conclude that until the fold system is fully understood it is difficult to discuss the small structures or the fabric. When the major and minor structures are mapped together, however, quite unexpected facts may emerge, such as the variations in plunge shown by the late lineations on opposite limbs of the Loch Monar synform or the Beinn a' Chapuill fold, and these facts may help to illumine the general geology. It seems most desirable that maps of metamorphic ground should contain all kinds of structural information; observations on axial plane foliation and the axial planes of minor folds are particularly valuable, since it is often easier to understand the linear structures in terms of the intersection of foliation and bedding than in any other way.

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The Petrogenetic Significance of the Contact Relationships of the Donegal Granite in Gweedore and Cloghaneely

By E. H. T. Whitten

Abstract

The "space problem" in north-west Donegal is analysed; structures of country rocks and granite-quartzite contacts, together with marginal granitization, suggest that two space-forming processes operated together. The inter-relationship of these mechanical and chemical processes in Gweedore and Cloghaneely suggests a dual rhythm within Read's (1949) granite series.

Introduction

WHEN the uniformitarian tool is not available for resolving the pressure, temperature, and chemical problems involved in granite parageneses, resort must usually be made to studying the "space problem" in the light of observational field data. Usually the space problem is solved by invoking essentially mechanical or chemical processes, or a combination of both operating together.

Mechanical production of space for emplacement of exotic "magma" involves either pushing country-rock aside, or alternatively removal of vast masses to lower levels, possibly to be assimilated by the advancing magma. The reality of such processes, or a combination of them, has often been proved (e.g. Wells and Wooldridge, 1931, Richey, 1948, and Martin, 1953). It has not always been possible to demonstrate *conclusively* that mechanical processes operated; then it is difficult to refute any alternative evidence suggesting chemical replacement. The dioritic migmatites described by Pitcher (1953*a*) are a case in point.

The main alternative to mechanical production of space is chemical transformation of country-rock. The numerous hypotheses all involve some variety of metasomatic "atom-by-atom" replacement; Reynolds (1946), King (1948), and Goodspeed (1940, 1948) among others, strongly support such theories.

As a contribution to this subject, factual data concerning the Donegal granite in Gweedore and Cloghaneely will be described. It is hoped to prove that mechanical and chemical processes and effects are not mutually exclusive but here operated together, being held in balance by the overall environmental conditions.

Introduction to the Rocks of North-West Donegal

The essential simplicity of the rock-types makes Gweedore and Cloghaneely an ideal area in which to study granitic contact relationships. Throughout northern Rosses (145090 [1]), Gweedore, and

[1] Localities are identified on Text-fig. 1 by six-figure grid references in the usual manner. (The British National Grid does not apply to Eire.)

Cloghaneely, strongly tectonized Dalradian quartz-schists of very constant characters border the granite.

The Donegal " granite " is a complicated composite dioritic-granodioritic mass which includes the migmatites of Trawenagh Bay (095090) (Gindy, 1953) and Thorr (123145) (Pitcher, 1953*a*). The latter possess a well-defined ghost-stratigraphy with varied metasedimentary relics in the sillimanite grade of metamorphism. Northwards these migmatites grade into quartzose microcline granite of the Gola island (087201) area. This Gola granite apparently resulted from metasomatic replacement of mobile para-autochthonous granodiorite confluent with the Thorr (123145) rocks. Apart from the Gola granite, all these granitoid rocks are conveniently styled " older " granites, being truncated by " younger " more acid and microclinic granites. The Rosses (145090) " younger " granites pierce the " older " granite (Pitcher, 1953*b*), and appear to be penecontemporary with the Ardara granite (080045) because the Main " younger " granite (150100) truncates both complexes (Pitcher, 1953*b*; Iyengar, Pitcher, and Read, 1954) as well as the migmatites of Trawenagh Bay (Gindy, 1953) and Thorr (Pitcher, 1953*a*).

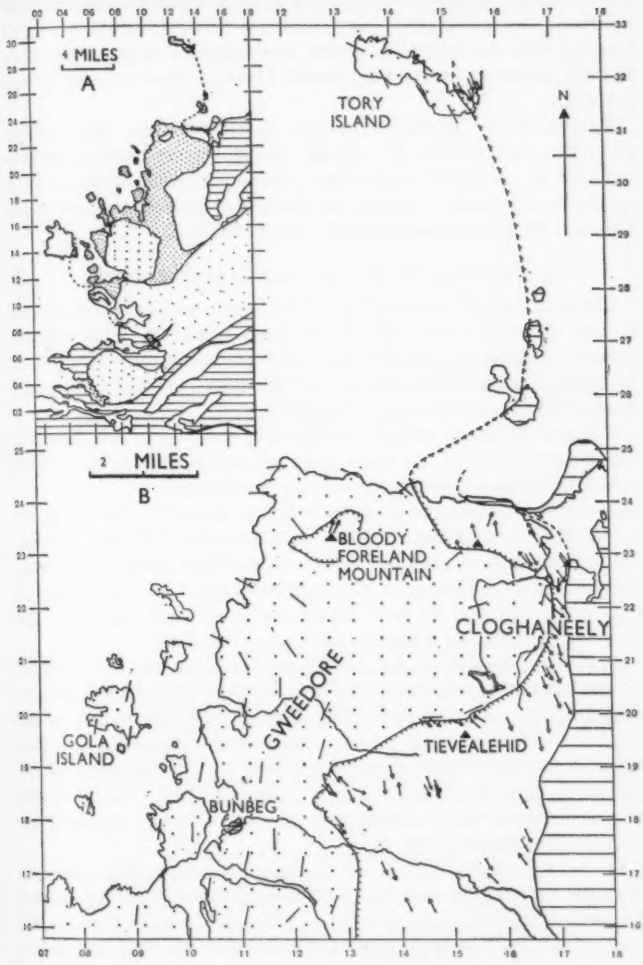
Evidence from the Country Rocks

(*a*) *General Petrology and Structure of the Dalradian Quartz-schists*

These rocks are continuous with the Crockator Quartzite of Thorr (Pitcher, 1953*a*); in Gweedore and Cloghaneely they comprise an uniform gently undulating sheet of strongly tectonized sub-vitreous well-jointed and usually massive quartzite. Flaggy horizons occasionally occur, but bedding is often difficult to discern. There is sufficient current bedding to prove lack of inversion.

Lineation is prominently defined (see Text-fig. 1B) by elongate quartz grains and occasional mullions and striations. The quartzite is a perfect girdle-tectonite, the girdle axis being parallel to the macroscopic lineations which are believed to coincide with a *b* tectonic axis. Constant development and orientation of these fabric elements suggests the original tectonization produced an affine structure within Gweedore, Cloghaneely, and northwards to Tory Island (145322). Subsequently slight warping occurred. Since Pitcher (1951, fig. 5) demonstrated the dominance of north-north-west lineation plunge east of Lough Keel (123148), a shallow synclinal warp with a fold-axis perpendicular to the *b* lineation is indicated by the plunge south of Clady River (115180) and north-east of Lough Nacung Lower (152168).

The quartzite is feldspathic to arkosic with an even grain-size (0·5 mm.). The scattered feldspar is almost entirely twinned and untwinned microcline, with very occasional plagioclase. Microcline



TEXT-FIG. 1.—A. The granite of north-west Donegal. "Older" granite (close stippling), and Ardara (080045), Rosses (145090) and Main (150100) "younger" granites. Dalradian quartzite (unornamented); pelitic and calc-silicate rocks (ruled).

B. Gweedore and western Cloghaneely showing trend of foliation in granite and plunge of quartzite lineations.

is essentially detrital and is interstitial to, or poikiloblastically enclosed by quartz. Sometimes meta-porphyroclasts of microcline (< 1·3 mm.) contrast with the interstitial grains, show signs of rolling, and occur in rude augen structures (e.g. beside Cromore Burn railway bridge (156170)).

Slender flakes of muscovite are fairly abundant, and biotite (Y = Z = dark brown, X = greeny amber; though almost entirely replaced by penninite) sometimes occurs. Quartz often partially envelopes the micas. Minute magnetite (or limonite) grains often delineate the original bedding and current bedding.

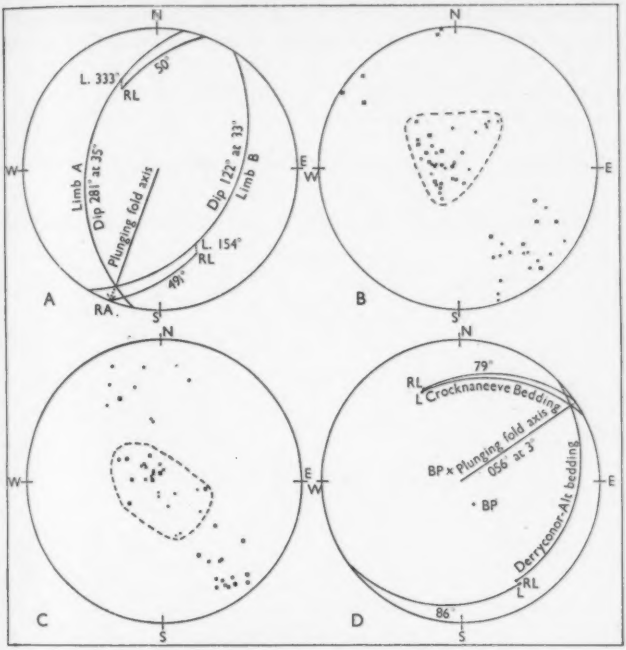
(*b*) *Warping of the Tectonite near the Granite Contacts*

The local dip, or increased dip, of the quartzite towards the granite is very apparent near many of the main contacts. This suggests marginal sagging consequent upon, and penecontemporaneous with, the regional granite emplacement, as if the affine tectonite " drooped " downwards towards the granite cauldron.

It is possible to test whether such folding was pre- or post-tectonic. For example, Text-fig. 2A gives proof of post-tectonic folding at the Keeldrum contact, since lineation on the stereographically " unfolded " quartzite is a continuous linear structure to within ½°. Similarly, the *b* axis plunges south-east at 20–30° on Tievealehid (152196) (Text-fig. 2B), whilst lineations at the northern marginal flank plunge north-west. The post-tectonic folding of this peripheral quartzite was about an axis roughly parallel to the trace of the axial plane shown by the quartzite bedding and a massive epidiorite (Text-fig. 3).

By contrast, in Meenanillar (128179) all lineations are nearly parallel to the inferred *b* axis, despite local steep dips towards the granite. Thus folding must have been pre-, or more probably, para-tectonic, and the steep dip extant prior to the granite emplacement. This particular structure may be correlated with the western flank of the Crockator Quartzite " upper block " (Pitcher, 1951, fig. 8) north-east of a shatter zone cutting that quartzite (Pitcher, 1953*a*, Plate XXVIII, and Pitcher, 1951, fig. 5).

The gentle outward dips of the quartzite round the Magheraroarty Mountain (150217) lobe of granite might suggest the granite up-domed the meta-sediments. Relevant lineation poles are shown in Text-fig. 2C. Generalized lineation poles pitch at 79° and 86° (Text-fig. 2D) about the rotated fold axis. Allowing for the diffuse nature of poles in the Crocknaneeve area, this virtually proves post-tectonic progressive warping about an axis plunging 3° at 056, rather than simple doming. This anticlinal axis is roughly parallel to the synclinal warp south of Clady River (see p. 26); thus this apparent doming is probably due to pre-granitic folding.



TEXT-FIG. 2.—Stereograms (lower hemisphere) of quartzite structures.

A. Keeldrum (165205) overturn: bedding planes of small fold and lineation (L) shown. Limb A = quartzite very close to granite; limb B = regional dip of quartzite near granite. Constructional rotation of fold axis to horizontal (RA), moves lineation poles to RL, with pitch at 50° and 49½°.

B. Overturn at Tievealehid (152196) (Schmidt projection), showing lineation poles and (within enclosed area) bedding plane poles. Crosses: localities in northern marginal flank of Tievealehid. Squares are areas less than, and dots areas more than, one mile from contact.

C. Folding near Crocknaneeve (Schmidt projection), showing lineation poles and (within enclosed area) bedding plane poles. Dots: main Crocknaneeve mass; Crosses: Derryconor (166230)–Alt (168225) area; Squares: Keeldrum (165205) area.

D. Folding near Crocknaneeve: generalized poles, derived from Text-fig. 2C, of bedding (BP) and lineations (L), which suggest simple folding about axis plunging 056° at 3°. Constructional rotation gives lineation poles (RL) with 86° and 79° pitch.

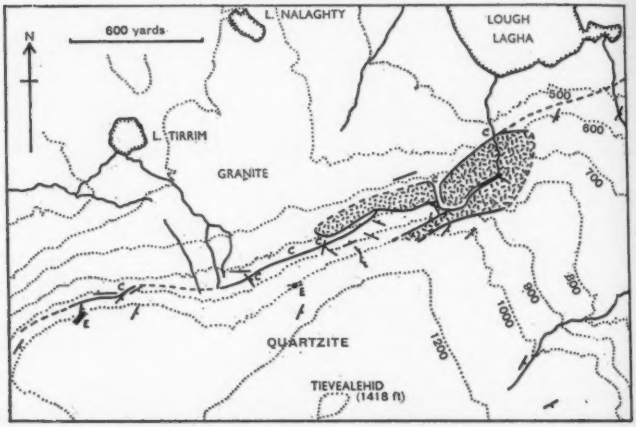
Analogous stereographic analysis proves that the Bloody Foreland Mountain (128234) quartzite is anomalous when correlated with adjacent areas; it is either a freely rotated " xenolith " or a relic of a different tectonic unit from the Crocknaneeve-Tievealehid mass.

Thus, there has been little post-tectonic movement, and much that occurred was pre-granitic. However, marginal folding at Keeldrum and Tievealehid appears to represent plastic "sag" down towards the granitic cauldron. There was no major disturbance of the country rocks due to granite emplacement.

Structural Features at the Granite-Quartzite Contacts

(*a*) *Tievealehid*

The contact north of Tievealehid is very transgressive, stoped, and



Text-fig. 3.—The Tievealehid granite-quartzite contact with trends of granite foliation and strikes of quartzite shown. C = actual contacts; E and ornamented area = epidiorite.

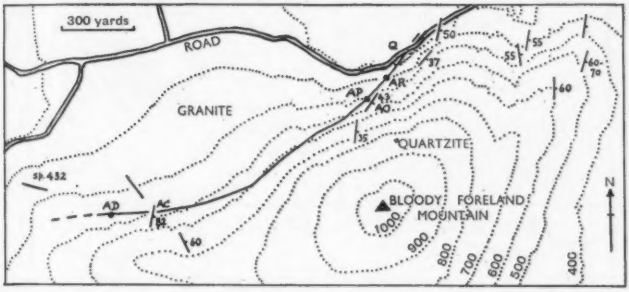
very steep to the north-north-west. On west Tievealehid the contact occurs at 930 feet O.D. (Text-fig. 3) and drops to 400 feet on Owentully (165212). Immediately south of Lough Lagha (157206) is a well-exposed incipient stope, where coarse-grained granite worked behind a 100-ft. thick block of epidiorite (Text-fig. 3). Another smaller and less well-exposed incipient stope occurs a quarter of a mile to west. A 300-yard long slab of epidiorite has been separated from the main country rock by a granite tongue. An intrusion breccia of small stoped epidiorite blocks separated by acid veins is exposed just beyond (to the east) the tip of the granitic tongue.

Almost due north of Tievealehid summit a migmatitic (lit-par-lit) contact zone occurs between massive granite and quartzite. A short distance farther west, and also due south of Lough Tirrim (147202), coarse-grained granite and shattered quartzite are in contact.

(*b*) *Crocknaneeve and Binanea Bay*

Since the Crocknaneeve contact is sensibly straight and descends from 350 feet O.D. to sea level at Binanea Strand (167225), the contact surface is probably nearly vertical. A sharp sub-vertical contact is confirmed by the coarse-grained lineated granite at the top of a north-east facing cliff-like exposure (165227) in Derryconor, since on the cliff flanks and to the north, quartzite outcrops.

Immediately west of this cliff intrusion breccia is well-exposed. Angular quartzitic fragments (12 inches diameter downwards) and occasional semi-pelitic or more micaceous quartzitic fragments are set irregularly in leucocratic granitic material. The mixed assemblage cannot be xenoblastic; it is essentially a product of intrusion.



TEXT-FIG. 4.—The Bloody Foreland Mountain granite-quartzite contact with trends of granite foliation and strikes of quartzite. Q = quarry.

The quartzite of Binanea headland (171227) is migmatized, the permeation becoming progressively more intense towards the contact. The cliffs on the west side of the headland excellently expose complex lit-par-lit structures developed in somewhat flaggy quartzite. The granitic sheets (3–6 inches wide) are either sub-horizontal or sub-vertical.

(*c*) *Tory Island*

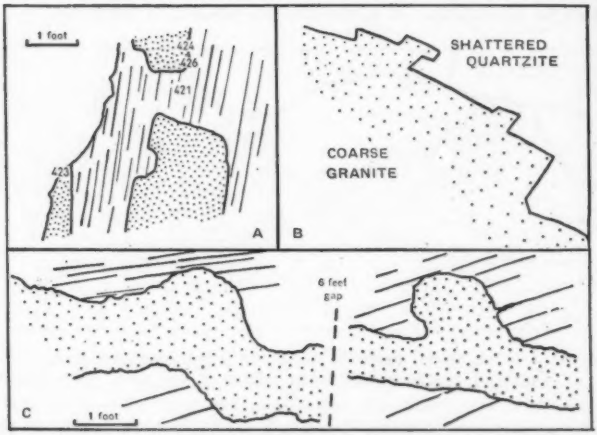
On Arderrill (153317) the contact is exposed in 200-ft. vertical inaccessible cliffs. So far as can be seen the contact is sharp, transgressive, and without migmatitic or fine-grained marginal rocks, although a few granitic veins invade the quartzite. No inland exposures exist. In the low tidal reefs near Torranaman (156313) the sharp contact is very irregular. South of the main contact several large randomly orientated quartzitic xenoliths are enveloped in coarse-grained granite; similar relationships occur at Rinardalliff Point Bloody Foreland (114243). Immediately east of the contact—beneath

the " crane " (156243)—quartzite is cut by several large sills and a network of interlocking micro-granitic dykes and sills.

(d) Bloody Foreland Mountain

The steep contact is exposed for almost a mile (Text-fig. 4), and shows very variable relationships. Sometimes coarse-grained granite is in juxtaposition with little-altered, shattered and stoped quartzite; at others the contact is more gradational and/or migmatitic. A little feldspathization of the meta-sediments is the only macroscopic evidence of metasomatism.

A transgressive junction is shown in the roadside quarry, where



TEXT-FIG. 5.—Typical granite-quartzite contacts on Bloody Foreland Mountain. A: Locality AC with specimen numbers indicated; B: Locality AR; C: Irregular transgressive " sill " in quarry.

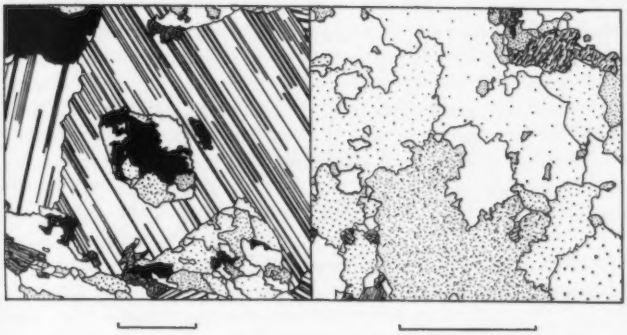
small granitic tongues (10 to 12 inches thick) and pegmatite veins are common in the marginal quartzite. At the west end of this quarry coarse-grained granite occurs at a scoured and stoped contact, which, like the occasional thin ($\frac{1}{4}$ to $\frac{1}{2}$ in.) pegmatite veins, follows bedding and joint planes of the quartzite.

PETROGRAPHY OF THE BLOODY FORELAND MOUNTAIN CONTACTS

Rocks at AC (Text-fig. 4) are representative of many of the contact rocks, and the three granitic lobes (Text-fig. 5B) may be assumed cosanguineous and contemporary. Specimen 421 (Text-fig. 5B) comprises 80 per cent quartz, with irregular grains of microcline and basic albite (much altered to " white mica "); small amounts of chloritized biotite and sericite occur. Closer to the granite (e.g. specimen 424,

28 per cent microcline microperthite, no plagioclase) the quartzite is more feldspathic and less micaceous. Granite actually against the contact has a very high colour index (includes 13 per cent biotite), and a feldspar content (35 per cent oligoclase, 9·9 per cent microcline) contrasting with that of the adjacent quartzite.

The actual contact is micro-migmatitic, and thin-sections show relatively large quartzitic areas separating more granitic portions. Jig-saw-like grain boundaries (Text-fig. 6A and 6B) in these quartzitic "xenoliths" are very distinctive, and contrast with the smoother



TEXT-FIG. 6.—Micro-textures at Bloody Foreland Mountain. Scales = 0·03 inches.

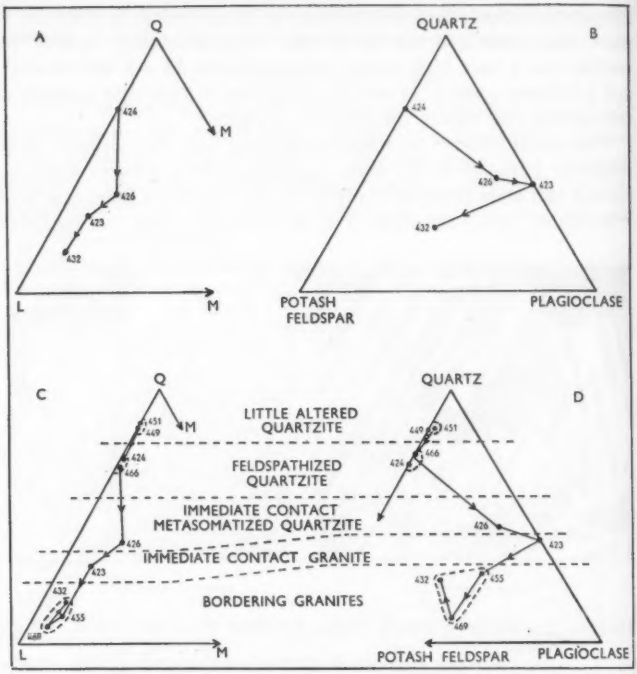
A. Quartzitic enclosure in plagioclase of contact granite—specimen 426, locality AC.

B. "Contact type" texture in quartzite—locality AO.

Quartz: stippled or black; Plagioclase: lamellar twinned; Mica: close cleaved.

outlines of the granitic quartz. These micro-xenoliths are usually rounded by resorption (Text-fig. 6A), and small biotites have often crystallized along cracks. These features must imply incorporation at an early stage of the granite's "cooling history".

There is a definite sequence of textural changes in the quartz. The ordinary tectonite possesses slightly interlocking texture. Towards contacts an intimately serrated interlocking texture develops—"contact type" texture. This must represent complete recrystallization; in consequence, adjacent grains often almost extinguish together, suggesting a stage towards porphyroblast development. "Simplification" of texture, with a trend towards ordinary granitic texture, follows incorporation of quartzitic fragments in granite, though easily detected relics of "contact type" are often preserved by xenoliths.



TEXT-FIG. 7.—Mineralogical and chemical variation across Bloody Foreland Mountain granite-quartzite contacts.

A. Contact AC: von Wolff diagram based upon data calculated from modes.

B. Contact AC: Partial modal variation diagram.

C. Composite Von Wolff diagram based on modes of the several localities.

D. Composite partial modal variation diagram of the several localities.

Whitten (1953) derived broad chemical variations from *certain* modal data. Text-figs. 7A and 7B demonstrate this technique applied to changes across the AC contact; biotite hornblende quartz-rich adamellite (specimen 432, Text-fig. 4) is used as control.

The sequence of changes outlined above is uniform at all contacts examined at Bloody Foreland, although the distance from the contact surface at which changes occur varies at each locality. The distance depends upon the degree of permeation and veining of quartzite.

At locality AP (Text-fig. 4) the quartzite (specimen 449) 40 to 50 feet from the granite has 15 per cent porphyroblastic microcline and

strongly developed "contact type" texture. The contact is not exposed to within 10 feet; the nearest quartzite (specimen 451) now contains 2·4 per cent plagioclase and 12 per cent microcline, whilst the "contact type" texture is a little simplified. The granitic rock nearest the contact is porphyritic microgranite with micrographic quartzo-feldspathic groundmass, small biotite, hornblende and plagioclase phenocrysts, and rounded "micro-phenocrysts" of quartz. Under crossed polars, the latter prove to be recrystallized quartzitic fragments, with the constituent grains almost in optical continuity. Occasional micro-autoliths (hornblende-biotite clots, about 1·5 mm. diameter) also occur.

Exceptionally, three or four micro-autoliths are cut by a thin-section, and they occur in both the regional granite and near-contact granites. They are not synneusis clots, but simulate early-incorporated xenoliths (possibly epidiorite). Frequent close association with quartzitic relics means that both cannot be remains of indigenous metamorphic rocks; at least one group must be wholly exotic. This evidence strongly supports a magmatic, rather than a transformational, paragenesis of the granitic rocks, and in particular, granite adjacent to the contacts.

Text-fig. 7C is a composite ternary diagram in which data from contacts AC and AP are compounded with modes for quartzite (specimen 466) and granite (specimen 469) respectively 1¼ feet and 4½ feet from a sharp contact at the west end of the roadside quarry.

Small granitic sheets were emplaced penecontemporaneously with the regional granite. Good exposures occur in the quarry. Although typically sub-concordant, they possess very irregular boundaries (Text-fig. 5C) with well-developed gradational contacts, so they cannot be simple fracture fillings without any replacement (cf. King, 1948, and Goodspeed, 1940, 1948). Replacement need not have been extensive, because the initial opening was probably mechanically produced. Within about 4 inches the following marginal zonation occurs:—

(i) Fine-bedded quartzite; slightly interlocking quartz with interstitial microcline.

(i)–(ii) Thin selvedge of biotite mainly decomposed to chlorite and magnetite.

(iii) Coarse-grained "contact type" quartzite; practically no potassic feldspar; abundant albite partially altered to "white mica".

(iv) Feldspar dominant; microcline content as zone (i); feldspars have more entire margins and "contact type" quartz texture patchily "simplified" causing slight embayment of feldspars. This recrystallized quartz possesses intense

" strain shadows ", which apparently represents imperfectly-welded small grains.

(v) Ordinary microgranite. " Simplification " of quartz outlines is marked, but palimpsests of " contact type " persist.

Hydrothermal metasomatism was concentrated at the zoned contacts because biotite microgranite farthest from the contact contains much less " white mica " and penninite.

To summarize, there has been progressive introduction of feldspar into a narrow zone of meta-sediments (Text-fig. 7D) at all contacts. The build up of feldspars is complicated by a marked culmination of plagioclase at the actual contacts (Text-fig. 5C). A weak culmination of mafic constituents (Text-fig. 7D) reaches its zenith in the marginal quartzite, and is slightly less marked in adjacent granite. The quartz content gradually increases to normal away from the less quartzose immediate contact granites. All these features may be attributed to activity of metasomatic " fronts " and " normal granitization ". On all scales this metasomatism simulates the geochemical changes leading to granitization invoked by Reynolds (1946). The order of most active penetration of ions into the quartzite appears to be K, Al, (Fe, Mg), Ca and Na. There is absolutely no reason to assume any volume increase in the marginal quartzite, or migration of materials beyond the K-Al culmination. Equal volume change would imply two-way migration across contacts, i.e. supply of Si to the granite.

Summary of Evidence from all the Contacts

The stoped transgressive contacts at Tievealehid, Derryconor, Tory Island, and Bloody Foreland Mountain, the intrusion breccias of Tievealehid and Derryconor, and the disorientated xenoliths at Rinardalliff Point (114243) and Torranaman (156313) indicate magmatic activity. Likewise, post-tectonic sagging of quartzite along part of the granite contact; if granite had resulted without the intervention of a mobile phase, it is believed that the tectonites would have been supported and prevented from sagging. Structural analysis proves dilation, or pushing aside of the meta-sedimentary envelope, has not occurred. Mobility of the granite is also proved by close association of micro-autoliths and quartzitic xenoliths.

Considerable variation in contact conditions in adjacent areas at Tievealehid, Crocknaneeve-Binanea and Bloody Foreland Mountain, is evidenced by alternation of sharp coarse-grained granite contacts, and migmatitic and/or gradational contacts. This suggests lack of marked temperature gradients across the contacts. Probably differential scouring and stoping by unchilled granite produced sharp contacts; more quiescent environments allowed more unhindered metasomatism.

Within small sills quiescent conditions enabled small-scale gradational contacts to develop.

Hence, both field relationships and microscopic studies suggest the granite was intrusive and magmatic. Equally conclusively the petrographic and chemical evidence indicates that advancing "fronts" resulted in metasomatism of the quartzite. Thus it is concluded that both granitizational and magmatic processes operated together in this area; the magma was not chemically "dead" and only capable of thermal metamorphism.

Petrogenetic Significance of the Contact Relationships of Gweedore and Cloghaneely

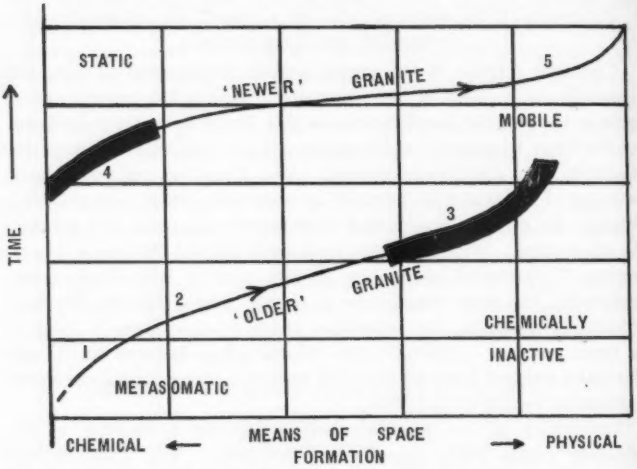
Chemical activity of the granite caused development of local and sporadic *basification* of the quartzite. Plagioclase enrichment of granite towards the quartzite proves this, because simple assimilation of the latter by granite could not cause such a culmination, since the quartzite only contains microcline. Also, there has not been simple soaking of the marginal quartzite by magmatic potassic granodiorite, because the marginal quartzite is depleted of microcline, and enriched in plagioclase. Whitten (1955) postulated that at Bunbeg a "basic residue" developed along the granite contact with basic metasediments, but since plagioclase is foreign to the Bloody Foreland Mountain quartzite, the oligoclase culmination cannot be part of a basic residue. Probably the mineralogical features at Bloody Foreland resulted from the standard sequence of granitizational fronts postulated by Reynolds (1946).

Uniformity of the quartzites makes accurate assessment of the absolute metasomatic transference possible. The characteristic resistance of quartzite to metasomatism and migmatization must account for the relatively "condensed granitizational sequences" and minor role of granitization in the genesis of this phase of the granite.

If a restricted portion of the described area had been considered in isolation, very different petrogenetic conclusions would have been derived. Thus, study confined to the Bloody Foreland Mountain quarries would reveal essentially metasomatic contacts, suggesting that the whole of the "older" granite arose from granitizational replacement. Alternatively, by isolated study of the breccias and contacts of Derryconor, or the sagged and stoped Tievealehid contacts, the space problem might have been solved by a simple mechanical hypothesis. It clearly emerges that within a single phase of the "older" granite two processes capable of solving the space problem operated together; a tension, or balance, existed between these forces.

In different complexes the balance between " mechanical " and " chemical " forces must vary in every proportion. Even in superficially simple granites it seems that both processes must be considered. It is generally accepted that a granitic series analogous to that outlined by Read (1949) exists, and that, in general, chemical and metasomatic effects decrease, and mechanical effects increase, with time (within the series). Clearly the present granite holds an intermediate position in such a series.

Post-crystallization metasomatism and recrystallization caused the



TEXT-FIG. 8.—The rhythm within the granite series. 1 = Trawenagh Bay area ; 2 = Thorr district ; 3 = Gweedore–Cloghaneely areas ; 4 = Gola granite ; 5 = Rosses granites.

quartzose potassic Gola granite (087201, Text-fig. 1) to develop in the solid state at the expense of the initial " older " granodiorite.[1] The Gola granite was not mobilized. It ante-dates the Rosses " newer " granites and is interpreted as a developmental or proto-Rosses granite (i.e. an early stage in paragenesis of " newer ", at the expense of " older ", granite). This implies production of microclinic intrusive granite from granodiorite " country rocks ", rather as dioritic migmatitic autochthonous granite can develop in meta-sediments. Thus these " chemical " and " mechanical " processes appear to exhibit a rhythm within the granite series. In relation to the space

[1] A detailed description of the Gola granitic rocks is the subject of a separate paper.

problem, both " older " and " newer " granitic rhythms have followed analogous courses. Text-fig. 8 attempts to relate the granitic rocks of Gweedore and Cloghaneely to this rhythm. To make the hypothesis clear in relation *to these areas*, some adjacent parts of the Donegal granite, which have already been described (Gindy, 1953, Pitcher, 1953 *a*, 1953 *b*) are tentatively included.

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On the Early Pebble Gravels of the Thames Basin from the Hertfordshire-Essex Border to Clacton-on-Sea

By S. Hazzledine Warren

Abstract

The erratic rocks of the early pebble gravels are similar to those of the Oxford plateau drift, and reasons are given for concluding that they belong to the drifts of the proto-Thames, and are earlier than the southward diversion of that river by an advancing ice-sheet. Comparisons with the constituents of the later deposits of the Clacton channel are also discussed.

Primary and Secondary Derivatives.—Erratics can be misleading when, as often happens, they are not in their primary association, but are secondary rederivatives from earlier drifts; in extreme cases a later gravel may be only a rearrangement of one of earlier date (Whitaker, 1877). Thus, the present-day shingle on the foreshore at Clacton is essentially a rearrangement of the "Holland gravel" of the local cliffs and contains little from any other source; the first collection sent to Mr. D. W. Baden-Powell included no item of difference from the early drift.

The Field Evidences.—It is noteworthy that more than a century ago Buckland (1823) traced the passage of the pebbles from the basin of the Severn into that of the Thames (mainly through the vale of Evenlode) and thence through the [early] Oxford drift into the [later] river-drifts around London (see also Baden-Powell, 1951). Among many later workers one may particularly mention: Salter (1905) who traced west country erratics into East Anglia, including the gravel cliffs of Holland-on-Sea; Sherlock (1924) who suggested that the proto-Thames swung north beyond Ware to discharge into the Wash; and Sandford (1929) who confirmed a west country source for the erratics of the Oxford drift. Following Sherlock's suggestion, I hope the wanderings of the early river over Suffolk and Norfolk will receive further attention from the evidence of the erratics.

Prestwich, Salter, and others have all noted the constant association in the lower Thames basin of Greensand chert from the Wealden area with the western erratics; and Wooldridge (1927 to 1938) identified the former courses of the southern tributaries carrying the cherts into the main river.

The following are some of the sections that have been studied, from the Hertfordshire border to the Essex coast: Westland Green (grid ref. 52/422.215, the levels of base and surface being respectively 338 and 352 ft. O.D.); and thence eastwards through the Dunmow district and Stansted to Silver End (52/817.193, 130 and 150 ft. O.D.), Ardleigh (62/049.283, 110 and 125 ft. O.D.), Thorpe-le-Soken

(62/192.213, 60 and 75 ft. O.D.), St. Osyth (62/138.160, 45 and 60 ft. O.D.), and Great Holland (62/203.192, 55 and 70 ft. O.D.) to the cliff sections at Holland-on-Sea and Clacton (levels 20 and 50 ft. O.D.). At both Ardleigh and Holland-on-Sea (at 62/207.163) there are deeper channels going down to about 20 feet below the general levels of the basal platforms as given above.

On the Tendring plateau, which extends from Colchester and Manningtree to the coast, there are a number of isolated patches of Red Crag which indicate that this area, although dissected by numerous small valleys, still retains much of its original form as the " plain of marine denudation " of the Red Crag sea. Its surface rises on a slight gradient from about 45 ft. O.D. at Clacton to 130 ft. in about 14 miles inland; over this area there is much gravel which is not arranged in terraces, but to a considerable degree consists of a complex of channel deposits of widely different dates but all coming within the same range of level (Warren, 1940, p. 10). For example, in addition to the proto-Thames gravels there is an Early Cromerian channel at Little Oakley (62/220.293 at 70 ft. O.D.) and within 1½ miles a Late Acheulian channel at Upper Dovercourt (62/241.313 at 75 ft. O.D.), an unidentified gravel with *Elephas* at Great Oakley (62/193.281 at 65 ft. O.D.) which is worth investigating as it may be related to the Cromerian channel, and a Clactonian gravel near Weeley (at 65 ft. O.D.) to be described later.

On the Frinton cliffs and also inland there are numerous solifluxion festoons of gravel and loam yielding Acheulian implements, most of which are of crude technique in marked contrast with the advanced skill of the Dovercourt industry. I noticed several festoons having a pear-shaped centre with the thin end upwards round which the original stratification had been folded up on either side. No glacial drift is known on the Tendring plateau, but it occurs immediately to the west and also in the Stour valley where a fall of cliff on the west side of Wrabness a few years ago exposed a notable section of glacial contortion banked against a hill that forms a promontory into the valley.

One of the Dovercourt implements (Late Acheulian) retains a portion of cortex which is striated. It has a thin ochreous patination under which it is grey; after careful comparison I feel little doubt that it is made from a grey tabular Lincolnshire flint from the glacial drift. I have seen no other glacial erratic on the plateau, but a stray Norwegian erratic was found below the submerged Neolithic surface at Stone Point, Walton.

The situation of the proto-Thames gravels on the Tendring plateau (= the Red Crag platform) gives an older limit of date to this drift; it is later than the emergence of the Crag sea-floor into a land-surface.

But this does not necessarily apply to proto-Thames drifts elsewhere, some of which may well be earlier.

I have seen no direct contact between the proto-Thames gravels and the fossiliferous early Cromerian channel at Little Oakley (Warren, 1940, p. 9), but I think the channel is cut through the gravel: at least the channel is not earlier, as it contains proto-Thames pebbles.

With reference to a later limit of date, the proto-Thames drifts have been extensively recorded as underlying the glacial deposits, and I have seen them overlain by Chalky-Jurassic till in many sections in the Cheshunt district, at Ongar, Tilekiln Green (near Bishop's Stortford), and at the Silver End pit. On the negative side, Baden-Powell's close search has failed to find any diorites, basalts, schists, or other erratics to correspond with those of the northern glacial drifts.

The Erratic Rocks.—I am greatly indebted to Baden-Powell for undertaking a study of the erratics, some of which were collected by himself, and the results are shown in the table, which he has generously passed to me for publication. K. P. Oakley has kindly assisted, particularly with the cherts; so also has F. J. North, who provisionally identifies a fragment of ribbed shell in chert as *Chlamys subacuta*, Lam., a Cenomanian species.

It will be seen from the table that the assemblage of erratics, here called " proto-Thames ", is mainly characterized by Bunter quartzites, white quartz, greywacke (blue volcanic ash), crinoidal chert, Greensand chert, and porphyritic rhyolites which are especially distinctive and important. A collection of these rocks has been deposited in the Department of Geology and Mineralogy at Oxford.

The grid reference of several of the sites has previously been stated; others are: Tilekiln Green (52/524.214) and three pits in the Colne Valley below Colchester where the gravels may possibly be rearranged, namely Wick (62/048,193), Wivenhoe (62/046.225), and Alresford (62/201.062).

To obtain the broad character of the gravels, apart from the rarer erratics, my method has been to take 400 pebbles of over 1 inch diameter and keep a chip of every non-flint stone for future reference. I found that on the Hertfordshire border the frequency of the Greensand chert is usually less than 1 per cent, but on the coast the cumulative effect of the southern tributaries brings it up to 3 to 5 per cent. Local conditions cause much variation with the various constituents: in the neighbourhood of Eocene pebble beds I have found up to 95 per cent of flint pebbles, but at a distance from the source these may be down to 20 per cent, with weathered flint up to 65 per cent. Quartz and quartzite each occasionally exceed 5 per cent but are usually less. Igneous rocks are only rarely as much as 1 per cent.

LIST OF ERRATICS

A.—From the proto-Thames gravels.
B.—From the later (post-diversion) drifts.

	A										B	
	Westland Green	Tilekiln Green	Stebbing (N. of)	Silver End	Wick, Colchester	Ardleigh	Wivenhoe	Alresford	St. Osyth	Holland Cliff	Clacton Channel	Weeley
Tertiary.												
Eocene flint pebbles [1]	x	x	x	x	x	x	x	x	x	x	x	x
Sarsen [1]	x										x?	
Hertfordshire Puddingstone [1]	x					x		x				
Jasperized flint [1]						x	x		x	x		
"Mahogany flint"											x	
Cretaceous.												
Echinocorys vulgaris						x			x			
Greensand chert	x	x	x	x	x	x	x	x	x	x	x	x
Greensand rock	x					x			x	x	x	
Trias.												
Bunter pebbles	x	x	x	x	x	x	x	x	x	x	x	x
Carboniferous.												
? Gannister						x			x			
? Millstone Grit						x			x		x	
Crinoidal chert	x		x		x				x			
Uncertain Age.												
Blue greywacke or Volcanic ash	x			x		x	x	x	x			x
White conglomerate	x	x						x		x		
White quartz	x	x	x	x	x	x	x	x	x	x	x	x
Hard green grit											x	
Tourmaline sandstone											x	
Igneous.												
Rhyolites	x	x		x	x	x	x	x	x	x	x	x
Volcanic agglomerate		x										
Grey granophyre											x	

[1] These are ubiquitous in all the drifts of Hertfordshire and Essex, but records are incomplete.

Fresh flint is always scarce in comparison with its abundance in the basement bed of the Red Crag.

Gregory (1922, pp. 30–5) states that the rhyolites are both more frequent and larger inland than near the coast: at Westland Green I found rhyolites up to 8 or 9 inches diameter, and white quartz up to 12 inches.

In my opinion the evidences stated in the foregoing are in favour of these gravels belonging to the proto-Thames river system, and unfavourable to the rival theory of a marine origin (compare Solomon, 1935).

The Clacton Channel Deposits.—The conclusion is now widely accepted that a lobe of ice blocked the ancient Thames valley and diverted the river to a more southerly course from near Marlow to the present estuary. The first and oldest terrace of the diverted Thames may well be the Winter Hill Terrace of Wooldridge (1927–1938), which is closely associated with glacial outwash. The Clacton channel (Warren, 1955), which is cut through the Holland gravel, is one among many others that are seen at or near the present intertidal level on the Essex coast; the deepest known (at Burnham) goes down to minus 125 ft. O.D. (Warren, 1951, p. 131).

Baden-Powell has examined the erratic rocks which I collected from a small quantity of gravel at the bottom of my Channel No. v at Lion Point, Clacton (see Warren, 1955). He reports that most of the rocks conform to the Oxford drift group, but there are three possible exceptions that are at present unknown in that connection. One is a grey microgranite, or granophyre, and another a glassy-looking bluish-green grit: neither of these rocks has yet been matched. The third is a grey tourmaline-sandstone which is similar to two erratics which have been found in the upper gravel at Hoxne.

There is no glacial drift near the channel, and nothing to give direct evidence of the relation of the one to the other, but Solomon (in Oakley and Leakey, 1938) thought that the heavy mineral grains were derived from the Chalky Boulder Clay.

It is clear that the gravel of the Clacton channel is mainly a rearrangement of the proto-Thames drifts, but it carries a larger proportion of significant additions than the present-day shingle of the Holland foreshore. That is to say, whereas the main bulk of the proto-Thames gravels (neglecting the scarcer constituents) consists of Eocene pebbles and weathered flints swept from the land-surface, the later gravels contain a much larger proportion of relatively fresh flint that was the result of the contemporary erosion of the chalk. It is evident that at the time of the proto-Thames drifts the areas of bare chalk under direct river erosion were comparatively small in much of the Thames valley.

This significant difference is well seen by comparing the gravel of the Holland and Clacton cliffs with the more nodular flint gravel of the later Thames channels which are cut through the older drift. Moreover, in the lower Thames valley there is a peculiar variety of flint with black inclusions instead of the more usual white. These inclusions were completed nodules at one stage, as they possess a thin white cortex, but later they became enveloped by bands of more chalcedonic and translucent flint. This variety readily acquires a "marbled-mahogany" patination which emphasizes its distinctive character; it is absent from the proto-Thames gravels, but common in the later Thames channels of Clacton.

The Weeley Gravel.—The pit near Weeley, previously mentioned, was closed soon after I found it, so my collection of artifacts is only a small one, but it includes no specimen that is not typical of the contemporary group of the Clacton channel. There are differences of frequency in the types, but this may be accidental; there is nothing to establish a well-characterized Acheulian industry, but comparisons with it are much more strongly marked than in the channel. I found one or two artifacts in the face of the section, and the site might be worth investigation (the position is at Hillhouse Farm, formerly called "Dakyn's Pit", 62/233.154). The gravel itself is a rearrangement of the earlier drift.

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FOREST VIEW ROAD,
LOUGHTON,
ESSEX.

Outline of Geology of the Dardanelles

By K. Erguvanli

(PLATE I)

Abstract

An outline of the geology of the Dardanelles is presented. Metasediments, chiefly marbles and schists, are cut by a granite and covered unconformably by Tertiary strata which include both sediments and volcanics. The Dardanelles is considered to be a drowned fault valley and in the south an echelon fault system is described.

I. Introduction

THIS study was carried out on behalf of, and with the help of a grant from the Institute of Mining Research and Study of Turkey (M.T.A.) in the summer of 1954, in order to complete the geological map of Turkey. For this purpose the 1 : 100,000 topographical map was used in the field. The author wishes to express his thanks to the above institute and to Dr. Francis Jones for help in preparation of this paper.

II. Geographical Position and Previous Work

The area studied includes both sides of the Dardanelles, i.e. the Gelibolu (Gallipoli) peninsula and the mainland immediately across the straits. The area is bounded by the Aegean Sea to the west and extends to the east as far as the small towns of Ayvalik and Bayramiç (see map).

Karagüllu (627 m.) and Çiğridağ (520 m.) to the south of Çanakkale, Yassitepe (374 m.) and Urendag (359 m.) in the Gelibolu peninsula, are the highest points; while the lesser heights include Alçi tepe (175 m.), known better to the British as Achi Baba. Küçük Menderes, Tuzla çay, Kepez dere, and Koça çay are permanent rivers; the Menderes is the Scameander of classical writers and passes near Troy. The earliest investigation was by Spratt who in 1858 discovered mammalian fossils at Erenkoy (Erengui), 15 km. south of Çanakkale, and general descriptions of these were given by P. de Tchihatcheff and J. Diller in 1867 and 1883 respectively. Specimens collected by F. Calvert were described by N. Neumayr in 1880 and a more detailed paper on the area was published in 1904 by Th. English. In 1917 W. Penck described the previous geological work in this area, and more recently (1944) the Institute of Mining Research and Study of Turkey (M.T.A.) published tectonic and geological maps to the scale of 1 : 800,000.

III. General Succession of the Rocks

The oldest rocks appearing at the surface are metamorphic, and these are overlain unconformably by rocks of Tertiary age including

both sediments and volcanics. Igneous intrusions are located solely within the metamorphic area, which includes marble, quartzite, and schists.

(*a*) *Metamorphic Rocks*

(i) *The Marble.*—Much of this would, perhaps, be more correctly termed crystalline limestone since the bedding is preserved, though the rock is not obviously fossiliferous. The true marbles are often pure white or greenish-grey, though purple and streaky varieties exist, and there is much brecciation. Thin sections of these marbles show, in addition to the carbonate minerals, grains of mica, quartz, and sphene (titanite), the mica suggesting that the limestone was dolomitic in origin.

(ii) *The Other Metamorphic Rocks.*—These rocks, which occupy a larger area than the marbles, include quartzites and mica-, sericite-, and graphite-schists. The rocks are older and are highly folded, with their main axes trending north–south. It is not possible to show the details of lithology and structure on a 1 : 100,000 map.

(*b*) *Pre-Tertiary Igneous Rocks*

These include granite and serpentine.

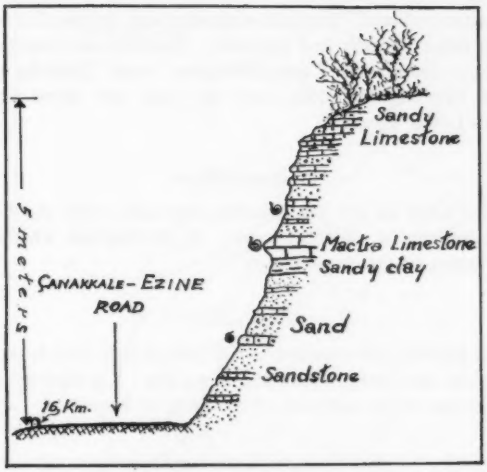
(i) *The Granite.*—With an outcrop of about 80 sq. km., this approaches the Aegean coast 50 km. south-south-west of Çanakkale. The mass reaches a height of 530 m. at Çigri dağ, near the village of Kestanbul, and in this paper is called the Kestanbul granite. The nearest town, Bergas, lies just north of the granite-metamorphic boundary, while good contacts are also seen south of the mass near Tabakli. Apophyses of the granite abound in the neighbourhood of Bergas and are well seen near the abandoned lead and iron mines there.

The contact rocks are rich in pyroxene and accessory apatite and sphene, and zircon is also found in the crystalline limestone at Tabakli. The granite varies from a medium to coarse, even-grained hornblende granite to a porphyritic type with crystals up to 5 cm. long of the pink and grey varieties of feldspar so often found in granites. Veins of aplite, pegmatite, and quartz occur within the main rock. In ancient times this granite was quarried and worked as an ornamental stone, and can be seen as big columns (monoliths 12·5 m. long and 1·70 m. in diameter) at Kocaali, near Kestanbul.

(ii) *Serpentine.*—A fault zone, trending north–south near the Aegean coast but swinging north-eastwards towards Çanakkale, contains lenticular masses of serpentine, the largest lying east of Troy near the village of Denizgorundu. This probably originated as a basic intrusion in the early stages of the fault movements.

(*c*) *Middle Eocene*

The Middle Eocene beds, which have a flysch facies, outcrop in the north of the area and reach the coast near Saros (Suvla) bay. They consist of conglomerate, sandstone, clay, marl, and limestone, all of a general yellowish-grey colour, with individual bands varying in



TEXT-FIG. 1.—Miocene strata on the bank of the road Çanakkale-Ezine, Km. 16.

thickness from 0·1 m. to 2·0 m. and sometimes showing ripple-marks. These strata are seen very well between Büyük (Great) Anafarta and Göldere. The prolongation of the Middle Eocene for some kilometres in a north-easterly direction along the Aegean coast was proved by the work of Z. Ternek (M.T.A. unpublished report, 1947, Ankara). Lenticles of limestone containing *Nummulites* sp. and *Operculina* sp. which occur in the andesitic tuffs exposed in the bank of the Koça çay 19–20 km. from Çanakkale, suggest that the eruptions were submarine.

(*d*) *Miocene*

Miocene formations extend in north-east and south-west directions on both sides of the straits. These have been already described by many geologists. Lithologically they consist of conglomerates, sands, marls, clays, beds of limestone, and sometimes gypsum bands, e.g. at Alcitepe, but there is no regular succession of these types. In certain

localities the limestone is highly fossiliferous, species of the genus *Mactra* being especially abundant, accompanied by *Unio* sp. Of the former, *Mactra caspia* Eich., *Mactra podolica* Eich., *Mactra* aff. *bulgarica* Toula, and *Mactra* aff. *dobrigiaca* Simion have been identified by Dr. L. Erentoz (M.T.A., Ankara). This limestone appears to be of the same age as that outcropping at Bakirkoy, west of Istanbul.

As is shown by the character of the fossils, the Miocene strata are partly marine and partly brackish-water deposits, the two facies passing into each other laterally and vertically. Fossiliferous localities occur at 16 km. along the Çanakkale-Ezine road (Text-fig. 1) and south of Eceabad (Maidos), and the beds are dated as Upper Sarmatian-Lower Pontian.

(*e*) *Post-Miocene*

On both sides of the Dardanelles, especially near the Gelibolu, there are terraces at different levels. It is uncertain whether these are of Pliocene or Quaternary age.

(*f*) *Alluvium*

Alluvial deposits are extensive in the river-mouths and in the valleys of the Küçük Menderes, Tuzla, and Koça çay. *Cardium edule* Linné has been found in the alluvium of the ruins of Troy.

(*g*) *Tertiary Extrusive Rocks*

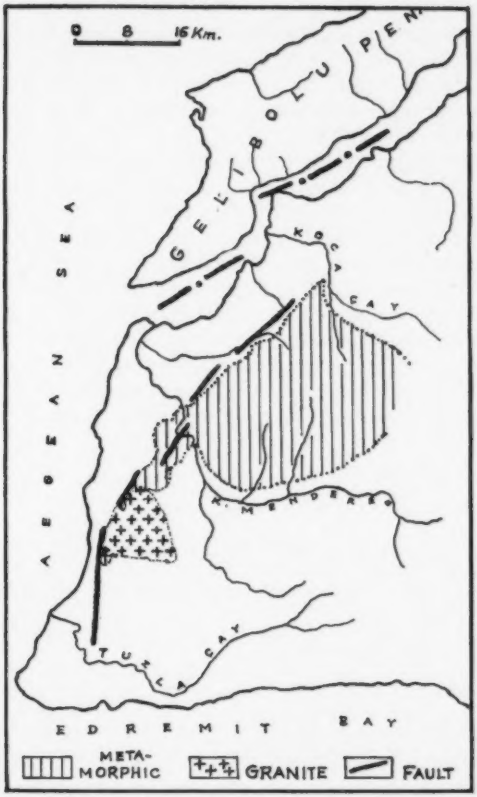
These include andesite, liparite, and basalt.

(i) *Andesite*.—Lavas accompanied by agglomerates and tuffs, largely of andesitic composition, form the land surface east of Çanakkale. The rocks are purple-grey in colour and are sometimes porphyritic. Sections show that the lava is fresh and is a hornblende-mica-andesite. The hilly country is dissected by the Koça çay and its tributaries, and in this valley, north of Terziler, lenticles of limestone containing *Nummulites* sp. and *Operculina* sp. are found enclosed in the volcanic rock material, showing that some of the eruptions were of Middle Eocene age.

(ii) *Liparite*.—Liparites are seen to the south of the Scameander valley, in the vicinity of the small towns of Ezine, Ayvaçik, and Gülpinar, and are exposed on the coast some 40 km. south of the Dardanelles entrance. In places they pass into dacite, trachyandesite, and andesite. Corresponding pyroclastics occur in some places. Grey-green clay, sandy clay, or lignite-bearing beds are intercalated with the extrusives. In one locality south of Gülpinar, at the village of Arablar on the Çinardere, 6 to 7 m. of white diatomite occur in

the liparite tuffs (and an analysis of this Arablar diatomite gave the following results: SiO_2 : 87·98 per cent, Fe_2O3 : 1·26 per cent, $Al_2O3 + TiO_2$: 4·97 per cent, Ca O : 1·08 per cent, MgO : 0·29 per cent, lost in ignition : 2·58 per cent).

(iii) *Basalt.*—The outcrops of basalt are less extensive, being seen



TEXT-FIG. 2.—Sketch-map showing the fault trends in the Dardanelles district.

only in the neighbourhood of Ezine. Interstratified with them is travertinous limestone of Miocene age and of lacustrine origin, a good exposure of which is found at Kiziltepe, others at Pinaroba, east of Troy. The basalt, which is vesicular and zeolitic, attains a thickness

of 35 to 40 m. Similar exposures of basalt with limestone occur at Taşvan ada (Rabbit Island), north of the Bozcaada (Tenedos).

IV. Tectonics

The metamorphic rocks which compose the basement are intensely folded, with fold axes running north–south, and the pattern is well seen between Çamlica and Geyikli. Prior to the deposition of Eocene strata severe faulting broke up the basement complex and determined its present limits to the west and north-west. An east–west fault is suspected, but not yet proved, in the Menderes valley. In general terms the basement is block faulted and it is not unlikely that the change in direction seen in the Dardanelles strait is due to parallel faults. The strait is usually regarded as a drowned valley, but is probably a drowned fault valley. Movement has not yet ceased, as is evident from raised beaches and terraces. North of Ezine a series of echelon faults with a N.E.–S.W. trend are plainly visible (Text-fig. 2). The Eocene strata which form the area north of Büyük Anafarta have a general east–west strike and a highly inclined or vertical dip. The adjacent Miocene dips south at not more than 20 degrees. South of Anafarta there is a shallow syncline with axes trending N.E.–S.W., which becomes almost horizontal as it nears the Alcitepe strata; the same happens in the case of the Miocene strata on the Asiatic shore near Kumköy.

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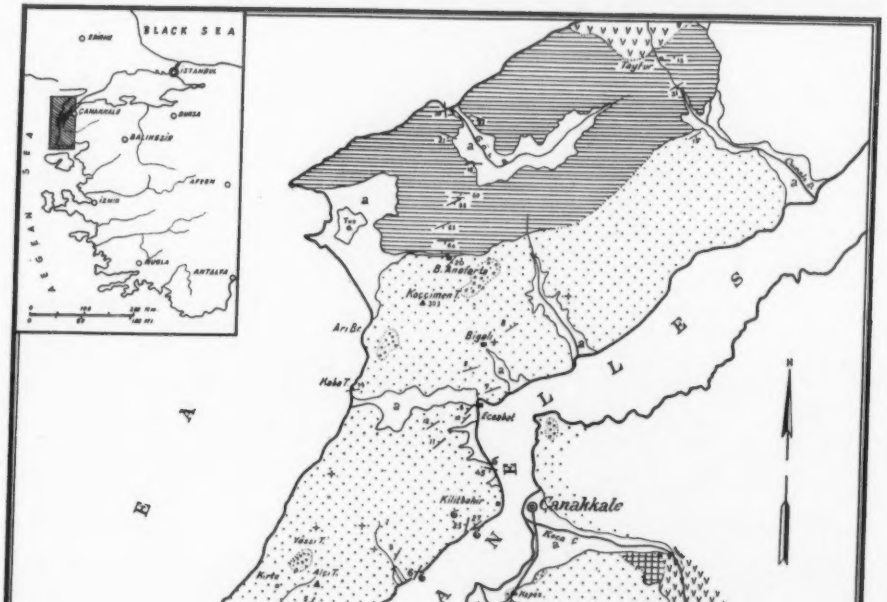
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ISTANBUL
ÇANAKKALE
BURSA
BALIKESIR
AYDIN
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MUĞLA
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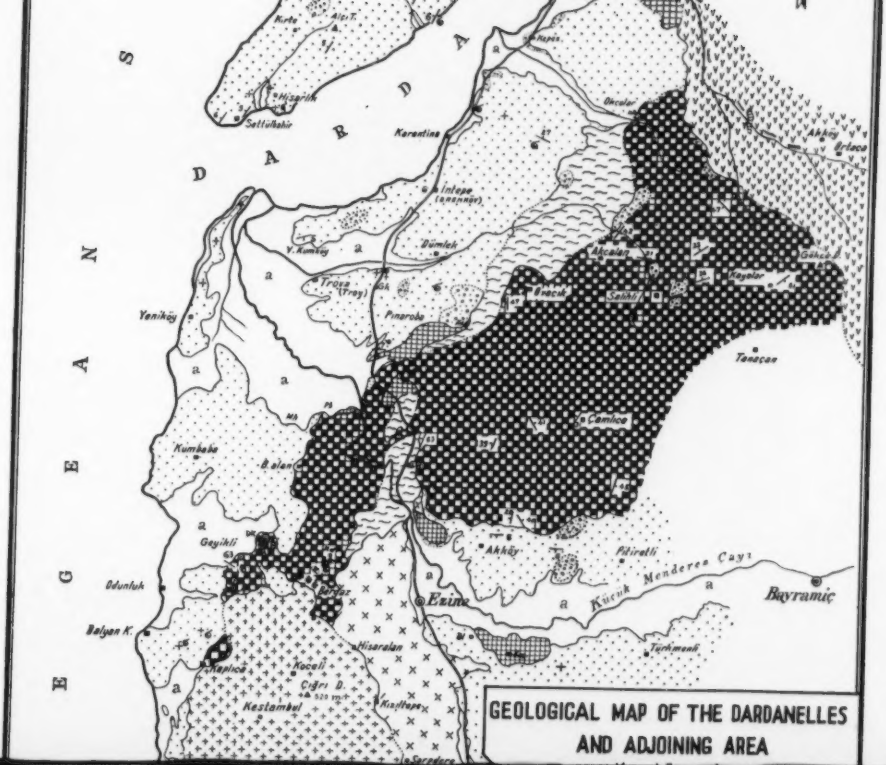
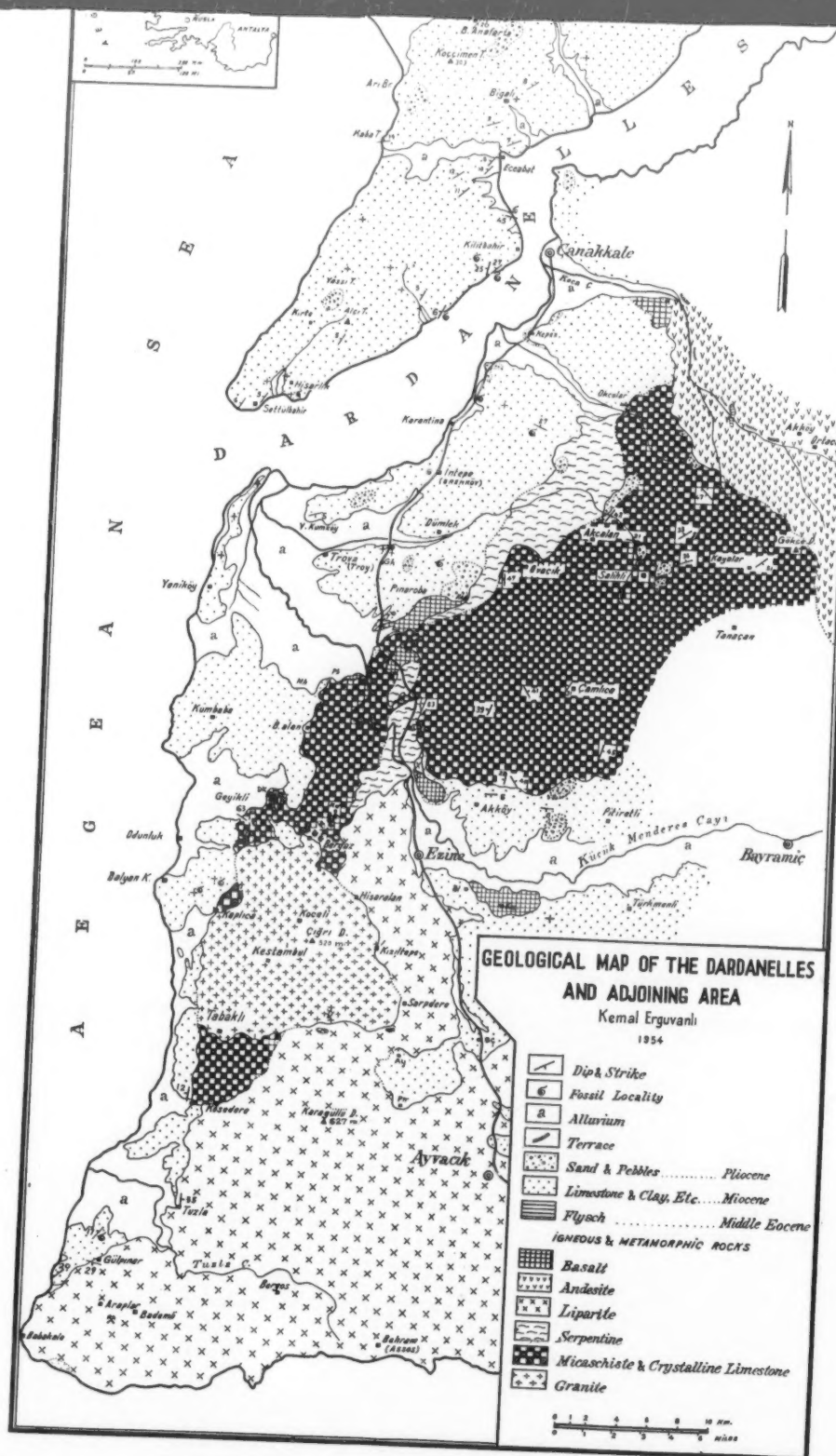


GEOLOGICAL MAP OF THE DARDANELLES AND ADJOINING AREA



GEOLOGICAL MAP OF THE DARDANELLES AND ADJOINING AREA.

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DEPARTMENT OF GEOLOGY,
TECHNICAL UNIVERSITY OF ISTANBUL.

EXPLANATION OF PLATE I

Geological map of the Dardanelles and adjacent area on the scale of 1 : 400,000.

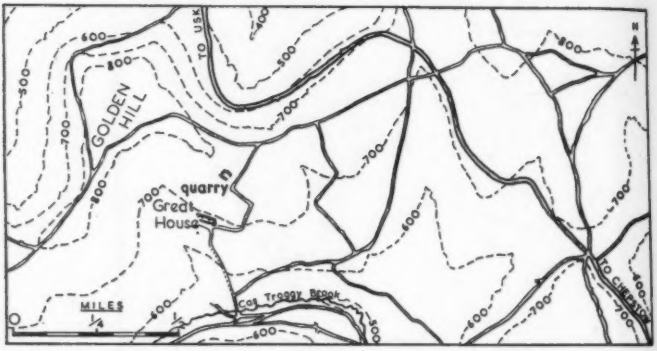
On a Volcanic Vent and Associated Monchiquite Intrusions in Monmouthshire

By V. A. Eyles and C. R. K. Blundell

Abstract

Quarrying activity adjacent to the well-known intrusion of monchiquite cutting Old Red Sandstone near Usk, in Monmouthshire (originally described by W. S. Boulton, in 1911), shows that the monchiquite proper is associated with an agglomerate-filled vent. Fossiliferous blocks contained within the agglomerate (first recorded by C. R. K. Blundell) show that the volcanic activity took place not earlier than in Lower Carboniferous time; and throw light on the former extension of the Carboniferous Limestone in this area.

In a letter to this magazine dated 19th October, 1954, Professor A. H. Cox (1954) recorded his view that the "monchiquite" exposed at Great House, four miles south-east of Usk, Monmouthshire (text-fig. 1), which was originally described by Boulton (1911),



Text-fig. 1.—Topographical map showing position of monchiquite quarry near Great House, Monmouthshire. (National Grid Ref. 431971, Sheet 31/49.)

is a "pipe-intrusion exactly similar to occurrences of kimberlite pipes in the Kimberley area of South Africa". In passing we may mention that a similar opinion was also expressed, verbally, by the late Professor W. T. Gordon when he visited the locality in about 1932. As stated by Professor Cox, a considerable quarry was opened up at Great House during or since the recent war. It is as a result of a detailed examination of the new exposures thus provided, made by the authors of this note early in 1954, that it is now possible to reach a definite conclusion regarding the nature and origin of the post-Old Red Sandstone igneous rocks exposed at Great House.

Not only has the new information that has been obtained placed their nature and origin beyond doubt, but it also indicates their probable age, and has the added interest that it throws light on the probable former extent of the Carboniferous Limestone in this area.

In 1911 Boulton suggested that the exposures of monchiquite then visible might form part of a dyke of considerable width, with a north-westerly trend; though he thought it more probable that they represented a " volcanic plug or bysmalith with an irregular sill-like extension in an easterly direction ". He qualified these suggestions by stating that the evidence then available was too imperfect to permit him to reach any final conclusion regarding the form and geological origin of the occurrence.

The exposures in the quarry may now be described. The quarry itself, which is entered from the south-east, is some 150 feet long, from south-east to north-west, and is about 100 feet wide and 50 feet deep. In the northern corner, for about 20 to 30 feet laterally, the walls of the excavation are formed of yellow sandstones with red and mottled marls of Old Red Sandstone age. At the north-west end of the quarry there is a small intrusion of fairly fresh, massive monchiquite of the type described by Boulton. It is somewhat irregular in outline, but extends more or less vertically up the wall of the quarry. Except for these localized occurrences of sediment and monchiquite the quarry walls, which are vertical, are everywhere formed of coarse, much decomposed greenish-grey to brown volcanic agglomerate. This rock appears to be that referred to in the past as " weathered monchiquite ". The monchiquite proper at the north-west end of the quarry cuts this agglomerate, and the agglomerate itself abuts against the sediments along a more or less vertical line. As far as can be observed the agglomerate is largely made up of blocks of monchiquite, but it also contains large crystals of mica and blocks of sediment, including a number of limestone and fine-grained dolomite, some of which are poorly fossiliferous. The appearance of the latter strongly suggested that they had been derived from the Carboniferous Limestone Series, and Dr. F. B. A. Welch informs us that lithologically they can be closely matched in neighbouring outcrops of the Carboniferous Limestone Series in the Caerwent Basin, two or three miles to the south-east, by crinoidal limestone occurring near the base of the Lower Limestone Shale Group and by the dolomites in the Lower Dolomite Group. In a block of crinoidal limestone Dr. W. H. C. Ramsbottom has recognized a cochliodont fish tooth, *Rhabdomeson* sp., and a Trepostomatous polyzoan, and these fossils, he states, are compatible with the conclusion that this block was derived from the lower part of the Carboniferous Limestone Series.

Thus, it is now clear, (i) that at Great House there is a volcanic vent, largely filled with agglomerate; (ii) that this vent is of post-Old Red Sandstone age, and (iii) that it must have been active some time after the commencement of the Carboniferous Period. Furthermore, the vent is situated between the Carboniferous Limestone outcrop of the East Crop of the South Wales Coalfield and that of the Caerwent Basin, west of Chepstow, approximately 10 miles from the one, and three miles from the other and two miles or so from the eastern margin of the Silurian rocks that form the core of the Usk Anticline. The occurrence of Carboniferous Limestone within the vent indicates, therefore, that at some time the Carboniferous Limestone sea must have approached close to, or even crossed, the Usk Anticline.

Concerning the vent itself, there seems no need to go as far afield as South Africa to find analogous occurrences. To one of us (V. A. E.) the Great House vent appears to be closely similar in mode of occurrence and petrological character to the numerous Permian volcanic necks that he and his colleagues in the Geological Survey of Scotland mapped some years ago in Ayrshire (Eyles and others, 1949). The agglomerate in these Ayrshire vents is characterized by the presence of blocks of the sediments that they pierce, by blocks of monchiquite and allied rock types, and by the inclusion of large crystals of the minerals commonly occurring as xenocrysts in the monchiquites. Frequently, too, the Ayrshire vents are cut by minor intrusions of monchiquite or related rock types. It might therefore be suggested that the Great House vent is of Permian age. Geographically the Monmouthshire volcano is situated much nearer to the Permian volcanic province of Devonshire than to that of Ayrshire, but comparison with the former area is more difficult because the Devonshire lavas differ considerably in character from the basic lavas associated with the Ayrshire vents (Tidmarsh, 1932), and no volcanic vents from Devonshire appear to have been described.

As an alternative, a Lower Carboniferous age is perhaps more probable, for, although fragments of Carboniferous Limestone are not uncommon in the agglomerate, no specimens of recognizable Upper Carboniferous rocks have yet been identified. Furthermore, extrusive basic igneous rocks of Lower Carboniferous age have been recorded nearer at hand, in several localities in Somerset, on the other side of the Bristol Channel. Indeed, similar vents of Lower Carboniferous age, sometimes with associated monchiquite intrusions, have been recorded in Scotland (Macgregor and MacGregor, 1948, p. 65).

By analogy with the Scottish occurrences it seems most probable that the monchiquite intrusion at Great House is genetically connected

with the vent which it cuts, and is of approximately the same age. It appears to be a minor intrusion of irregular form such as often occurs associated with the Permo-Carboniferous vents in the Midland Valley of Scotland, but its exact extent is not known. Taking into account the exposures seen by Boulton (1911, p. 461) it seems likely that the intrusion may be somewhat larger than the present exposure suggests. Nor is the full extent of the vent itself known, since its margin is only partly exposed. The possibility that the monchiquite may be continued to the north-west as a dyke cannot be ruled out, for the late Dr. R. W. Pocock, who surveyed this area for the Geological Survey, briefly recorded (1940, p. 30) an occurrence which he described as a " further outcrop " of the dyke at " Golden Hill " at a point two miles north-west of the original exposures. This outcrop occurs two and a half miles south-east of Usk, near Llanowell, 150 yards south of Glen Court House. A recent visit to this locality confirmed the presence there of a vertical dyke, some 15 feet across, cutting Old Red Sandstone, in a small quarry just below the scarp formed by the *Psammosteus* Limestone. It consists of typical monchiquite, similar to that occurring at Great House, with xenocrysts of mica and pyroxene, and cognate xenoliths of ultrabasic material. The outcrop extends for 20 or 30 yards along a roughly north-west to south-east line and a continuation of the dyke in a south-easterly direction would pass through or very close to the Great House vent, but no exposures have been found in the intervening ground. The position of the Llanowell dyke and of the monchiquite intrusion at Great House are both shown on Sheet 2 of the 10-in.-to-the-mile Geological Survey map of Great Britain.

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A Provisional Reclassification of Granite

By F. Chayes

Abstract

The term " granite " could be usefully reserved for massive or weakly oriented plutonic rocks of colour index less than 20 per cent and quartz content between 20 per cent and 40 per cent by volume. A symbolic classification of rocks meeting these requirements is presented. The various classes are based on the relative proportions of plagioclase and alkali feldspar, and sub-classes based on the ternary dominance ratio quartz-alkali feldspar-plagioclase are also proposed. The symbols are simple and easily remembered. A few of the common names now in use are retained for class designations.

Suggested Limits for the Modal Composition of Granite

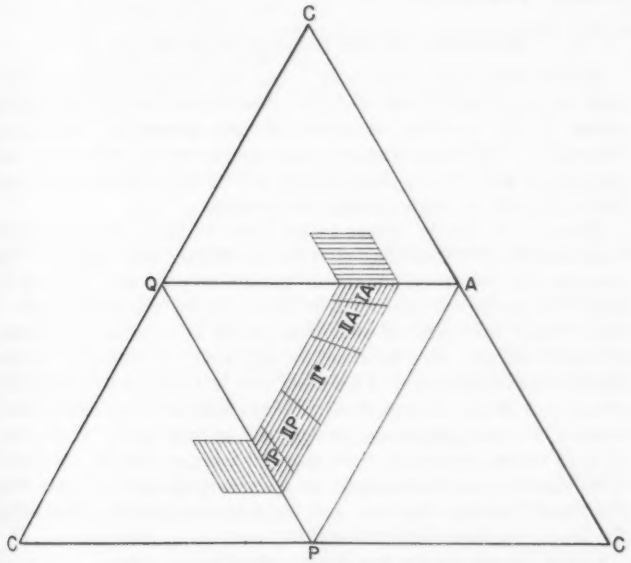
THE words we use as the common names of granite are hardly more than names assigned to pigeonholes in classifications. They are used differently in different classifications and I think no one classification uses all of them. Unless the choice of name is based on reliable modal analysis of adequate samples, furthermore, there is an excellent chance that it will be misused regardless of which system the user adopts. One man's adamellite is another man's granodiorite, and we rarely know whether the difference is real or nominal.

Although there is much to be said for the notion, probably few geologists would adopt, or even tolerate, an entirely new suite of varietal names for rocks of the granite group. As an alternative, I should like to propose a simple symbolic classification based on reasonable compositional boundaries for the general term granite. These limits are drawn from modal analysis of specimens collected by myself over the past eight years, but an examination of the journal literature will soon persuade anyone that a rock whose composition does not fall within them is very rarely called granite. The name granite could usefully be reserved for massive or weakly oriented rocks of colour index [1] less than twenty, and containing not less than 20 per cent nor more than 40 per cent of quartz by volume.

There will probably be little dispute about the upper limits of colour index and quartz content. Intrusive rocks of colour index greater than twenty are almost never called granite, and sizeable intrusive masses containing more than 40 per cent of quartz are virtually unknown. The lower limit of quartz, on the other hand, is rather higher than that suggested in most classifications, chemical or mineralogical. Except in tabulations compiled by systematists, however, a quartz content of less than 20 per cent by volume almost

[1] In the sense of Shand (1943, p. 196), i.e. denoting, in volume per cent, everything other than quartz, feldspathoids, and feldspar.

always results in the use of names other than granite. Iddings, for example, sets the lower limit of normative quartz in granite at 12·5 per cent, and his collection of 142 norms contains eighteen in which normative quartz is less than 20 per cent. Thirteen of these were given names other than granite in the original descriptions, however, and of the five which were originally called granite only two carry less than 18 per cent of normative quartz; the *modal* quartz of the other three is in all likelihood above the proposed



TEXT-FIG. 1.—Volume assigned to granite in the tetrahedron quartz (Q), plagioclase (P), alkali feldspar (A), colour index (C).

minimum of 20 per cent. Sampling and measuring techniques used in modal analysis are still so uneven that one hesitates to place much weight on conclusions drawn from tabulation of modes. Still, it may be worth noting that of the more than 350 modes listed in Vol. II of Johannssen (primarily the plutonic members of the granite, granodiorite, and tonalite families), the name granite was originally applied to only eighteen in which quartz falls below 20 per cent. Five of these, from scattered localities, are the work of a single petrographer. A couple of others I know from my own experience are wrong. Geologists who are at all concerned about the composition of rocks

rarely—and in recent times almost never—apply the name granite to a rock containing less than 20 per cent of quartz by volume.

Text-fig. 1 shows the projection of the volume assigned to granites by these limits in the tetrahedron quartz (Q), dark minerals (C), alkali feldspar (A), plagioclase (P). The population density would be virtually nil in the region $15 < c < 20$, and low in the region $10 < c < 15$. For practical purposes, a classification of granite must stand or fall by its treatment of the bounding face quartz—alkali feldspar—plagioclase.

Subdivision of the Bounding Face Q—A—P

(*a*) *The Distinction between One- and Two-feldspar Granites.*—Perhaps the most prominent distinction between members of the granite group is the partition of albite between plagioclase and alkali feldspar. Important textural and mineralogical differences are associated with this partition, and the factors governing it are probably quite as much physical as chemical.

Granites are nearly always rather poor in lime, and from their mineralogical definition they must be consistently rich in alkalis. On occasion the excess of soda over potash may be extreme, but in unaltered granites the converse is rarely—in my experience never—true. When the excess of soda over potash is extreme, the amount of alkali feldspar may be small or negligible. Commonly neither alkali is in extreme excess of the other, and it is here that the partition of albite is of crucial importance. If the bulk of soda enters alkali feldspar, the total plagioclase content will be very small. If the bulk of soda enters plagioclase both types of feldspar will be abundant. With regard to their occurrence as *major* constituents, we may thus distinguish between the one- and two-feldspar granites, designating the former by I and the latter by II.

Under I we shall have two classes, namely:—

IP—in which alkali feldspar is not a major constituent.
IA—in which plagioclase is not a major constituent.

Data regarding the modal composition of one-feldspar granites are utterly inadequate, and in their absence we have to make a rather arbitrary distinction between types I and II. The total feldspar content of a granite will ordinarily lie between 50 and 70 per cent, so that if the lines which separate II from IP and IA are set at $A/P < 1/9$ for IP and $A/P > 9/1$ for IA, the subordinate feldspar will rarely amount to more than 7 per cent of a type I granite. This is a quantity directly comparable to that in which the micas, which serve as our standard for minor essential constituents, ordinarily occur.

Subdivision of type II is more troublesome, for the range of composition involved is very much broader. Fortunately, granites of type II are common, and modal analyses of them are accordingly more abundant. In fact, the limits proposed by Lindgren for Brögger's quartz-monzonite group enclose all but five of the thirty-four mean values for my collection of two-feldspar granites. These well-known limits are:—

A/P > 1/2, separating Lindgren's granodiorite from Brögger's monzonite group, and

A/P < 2/1, separating the monzonites—in Lindgren's view—from the " true " granites.

The three classes of type II granite are designated by:—

IIP—in which $9/1 > P/A > 2/1$,

II*—in which $\dfrac{\text{dominant feldspar}}{\text{subordinate feldspar}} \leqslant \dfrac{2}{1}$,

IIA—in which $9/1 > A/P > 2/1$.

The types and classes of granites so far defined are shown in Text-fig. 1.

(*b*) *Relative Dominance of the Major Minerals.*—If we designate quartz by 1, alkali feldspar by 2, plagioclase by 3, and mention these index numbers in the order of abundance of the minerals they represent, we arrive at six different major mineral dominance indices, one for each of the possible orders of abundance, viz.:—

(123) quartz > alkali feldspar > plagioclase
(132) quartz > plagioclase > alkali feldspar
(213) alkali feldspar > quartz > plagioclase
(231) alkali feldspar > plagioclase > quartz
(312) plagioclase > quartz > alkali feldspar
(321) plagioclase > alkali feldspar > quartz

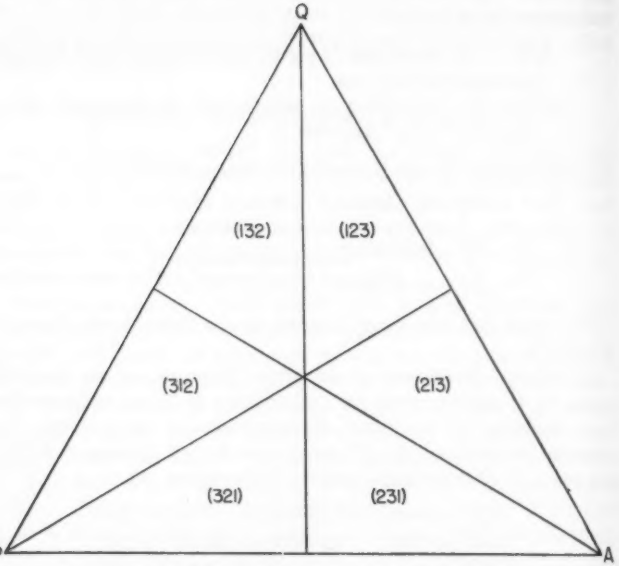
The regions characterized by each of these indices, the sub-classes of the classification, are shown in Text-fig. 2.

(*c*) *Types, Classes, and Sub-classes of Granite.*—Text-fig. 3 is simply a combination of Text-figs. 1 and 2. It shows at once that only one order of abundance is possible in each of the classes of type I. IP granites will always belong to the sub-class (312) and IA granites will always fall in sub-class (213). There is, therefore, no need to include the dominance index in the symbol of type I granite.

Similarly, granites of class IIP will nearly always belong to sub-class (312) and those of class IIA will nearly always fall in sub-class (213). For the very rare cases of IIP (321) and IIA (231), the dominance index should be included in the symbol. (So far I have

found no example of either.) Otherwise the dominance index may be omitted in IIA and IIP exactly as in IA and IP; in its absence P implies sub-class (312) and A implies sub-class (213).

In the very common granites of class II*, however, all sub-classes can and do occur. The dominance symbol here adds considerable



TEXT-FIG. 2.—Dominance symbols (1, quartz; 2, alkali feldspar; 3, plagioclase) in the bounding face of the granite tetrahedron.

information and wherever it is known it should be substituted for the asterisk.

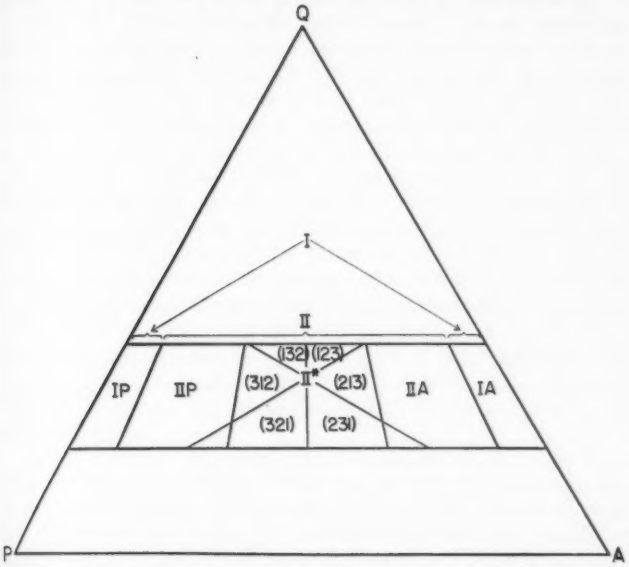
COLOUR INDEX AND DARK MINERALS

The symbols so far suggested are entirely concerned with quartz and feldspar and tell nothing of the dark minerals except that they constitute less than 20 per cent of the rock. But if information sufficiently precise to permit use of these symbols is available, the colour index will be known with the same precision. Wherever possible, it should be inserted as a post-subscript, thus

$$\mathrm{II}(321)_{10}.$$

The essential dark minerals will ordinarily be hornblende, biotite,

muscovite, or one of the pairs biotite-muscovite, biotite-hornblende. (Minerals ordinarily present only in accessory amount will occasionally be as abundant as the micas, or more so.) The essential minor minerals may be indicated in the symbol by insertion of their initial letters to the left of the Roman numeral. If they have not been



TEXT-FIG. 3.—Types, classes, and sub-classes of the proposed granite classification.

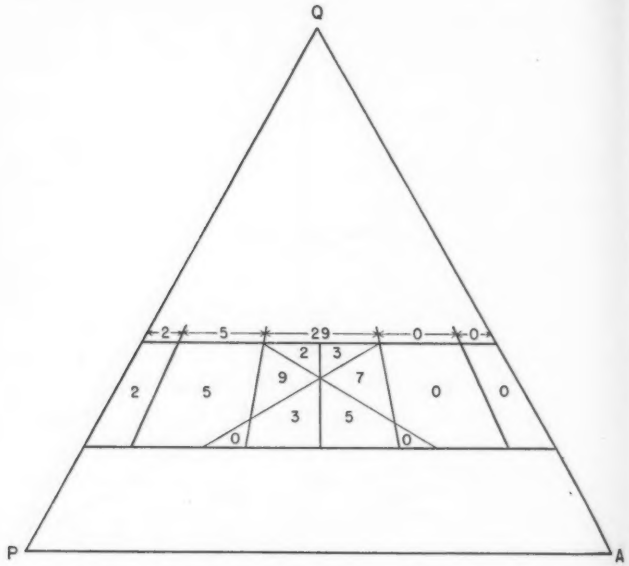
separately tallied in the analysis, they are to be listed on a single line. If they have been separately tallied, the dominant one forms the numerator of a fraction whose denominator is the other. Thus, finally:—

bmIIP_9 stands for a biotite-muscovite two-feldspar granite of colour index 9 in which plagioclase is more than twice as abundant as alkali feldspar, but the relative importance of biotite and muscovite is unknown;

b/mII$(213)_{11}$ represents a biotite-muscovite two-feldspar granite of colour index 11, in which quartz is intermediate in amount between alkali feldspar and plagioclase, the excess of alkali feldspar over plagioclase is less than two-fold, and biotite is more abundant than muscovite.

Relative Abundance of the Different Classes of Granite

The relative abundance of the different types and classes of granite is of critical importance but the present state of our knowledge of modal composition scarcely permits a satisfactory evaluation of the situation.



Text-fig. 4.—Number of examples of the various classes and sub-classes of granite so far described (by F.C.).

Text-fig. 4 is a graphical summary of results for specimens collected and analysed by myself in the course of the last eight years. Reasonably good average values are available for thirty-six masses, four from Southern California, five from the south-eastern United States, four from Minnesota and South Dakota, three from Texas, one each from Britain (Carnmenellis) and France (Lanhelin-St. Pierre), and fifteen from New England. The New England results were published some years ago (Chayes, 1952) and I hope at a later date to present a detailed description of the remainder. I have, in addition, analysed a number of Japanese specimens sent to me by Dr. H. Kuno and a suite of specimens from the granite of the Sierra de Guadarrama, Spain, given me by Dr. José Fuster Casas. A description of the latter has been published (Chayes, 1955); the group average falls in

class II(312). The Japanese specimens, from two Tertiary masses west of Tokyo City, fall in IIP or IP.

The absence of entries in IIA and IA is partly because of difficulties encountered in the staining of cryptoperthitic feldspar, but I believe that rocks of both classes are rather uncommon. From the description given by Warren (1913) the granite of Quincy, Massachusetts, is probably IA, though occasional rather extreme variants might fall in IIA. Entirely similar granite occurs in large quantity north of Boston, at Peabody and on Cape Ann. The granite of Conway, New Hampshire, may well be of this type, though suitable modal analyses of it do not appear to have been published. The coarse hornblende granite which forms the bulk of the island of Mt. Desert, Me., contains scattered clusters of plagioclase, but its average composition probably lies in or near IA. (The finer-grained biotite granite of the island is of type II(213) and contains no hornblende.) Tuttle's (1952) description of the Deloro granite, which lies west of Madoc, Ontario, places it in type IA and it is entirely possible that other examples will be found in the Thousand Island area, to the east. Tuttle (1954) also shows that portions of the marginal facies of the Beinn an Dubhaich granite on the island of Skye belong in IA, though the mass as a whole is probably well within IIA. Probably most of the granites of the British Tertiary lie in one or other of these two classes.

This is a rather imposing list, but considering that only four (Quincy, Deloro, Mt. Desert, Arran) turned up in the routine aspects of my own sampling, during which well over sixty bodies of types II*, IIP, and IP were located, I am inclined to think that granites of types IIA and IA are on the whole rather scarce. All three examples from the eastern United States are so coarse that during the initial stages of my sampling I decided not to work on them at all. So far as I know there is no sizeable mass of medium- or fine-grained one-feldspar granite in the eastern United States. The two-feldspar granites, on the other hand, occur in any grain size one may wish to name; for each of the examples of IA or IIA excluded from my detailed sampling because of grain size, several masses of II* or IIP met the same fate.

Granites of type II* are by far the commonest in my sample and I believe this is probably true in the lithosphere as well, though there the situation may not be so extreme. In particular the bulk of the rock called granodiorite and much of that called quartz-diorite in the Cordilleran area of the United States probably falls in IIP. Further, although IP granite is rare in the eastern and central United States, and the known bodies are very small (e.g. Bethel, Vermont; Warman, Minn.), it occurs in large quantity in Southern California. The

" tonalites " of the Perris block, for instance, which are of type IP, probably comprise a volume of rock several times as large as the total volume of all the IA granites mentioned above.

Suggested Nomenclature for Granite

The term *granite* should be reserved for massive or weakly oriented rocks in which C.I. $\leqslant 20$ and 20 per cent $\leqslant$ quartz $\leqslant 40$ per cent; it should be applied without mental reservation to any rock possessing these qualifications, and it should not be applied to other rocks. The group is conveniently divided into two principal types, of which one contains two classes and the other three:—

I.—The one-feldspar granites, in which the ratio dominant feldspar/subordinate feldspar $\geqslant 9/1$.
IA—in which the dominant feldspar is alkali feldspar.
IP—in which the dominant feldspar is plagioclase.

II.—The two-feldspar granites, in which the ratio dominant feldspar/subordinate feldspar $< 9/1$.
IIP—$9/1 >$ plagioclase/alkali feldspar $> 2/1$.
II*—dominant feldspar/subordinate feldspar $\leqslant 2/1$.
II(123)—quartz > alkali feldspar > plagioclase.
II(132)—quartz > plagioclase > alkali feldspar.
II(213)—alkali feldspar > quartz > plagioclase.
II(231)—alkali feldspar > plagioclase > quartz.
II(312)—plagioclase > quartz > alkali feldspar.
II(321)—plagioclase > alkali feldspar > quartz.
IIA—$9/1 >$ alkali feldspar/plagioclase $> 2/1$.

For granites of type II the term " two-feldspar granite " followed by the appropriate symbol in parentheses provides a simple, unambiguous designation, but separate class names may be desirable for II* and IIP. If there were any possibility that they would gain wide acceptance in this sense, one might be tempted to suggest that adamellite be used for II* and granodiorite for IIP. Except for the upper and lower bounds for quartz content this usage would conform closely to Lindgren's suggestion of 1900.

The term " tonalite " is used by some writers for what is here called granite of class IP. But others use quartz-diorite for exactly the same purpose, and both terms have been redefined and misused so often as to be virtually worthless. Both are often used for rocks much too poor in quartz and high in colour index to be regarded as granite. The best description of a sizeable IP granite known to me is that of Goldschmidt (1916), who suggested the name trondhjemite. The word is troublesome to spell and not widely used, but has never

been redefined, discredited, or, as far as I know, systematically misused.

For the granite group as defined here, no further nomenclature seems essential. Some of the names now used rather loosely for members of the group—tonalite, quartz-diorite, quartz-monzonite—might properly be reserved for rocks carrying less than the proposed minimum of quartz, that is to say, for rocks which are *not* granite. In the case of quartz-monzonite and quartz-diorite this would have very nearly the effect of restoring the original meaning. And for tonalite it would conform pretty well to current usage.

Until good examples of IA and IIA are properly sampled and analysed there seems neither justification nor advantage in suggesting place names as proxies for the symbols. (Most of Tuttle's specimens of Beinn an Dubhaich are taken from very near the margin of the mass. The suggestion above that the bulk of the mass falls well within IIA is an inference based on the fact that he records an average plagioclase value of 10·5 per cent despite the fact that "plagioclase is absent in several specimens".)

The names so far proposed fit into the system as follows:—

(1) Granite.

I.—The one-feldspar granites.

IP—trondhjemite.

IA—?

II.—The two-feldspar granites.

IIP—granodiorite.

II*—adamellite.

IIA—?

(2) Rocks which are not granite—quartz-diorite, quartz-monzonite, tonalite, quartz syenite, banatite, etc.

The only anomaly in the naming is adamellite: the word is used in very nearly this sense by most of those who use it at all, but from published analyses we still do not know whether the type adamellite is in fact a II* granite.

The entire classification invites attack on the ground that it ignores the An content of plagioclase, a staple of granite classifications for almost a century. The omission is intentional. The plagioclase of IP and IIP granite may be more calcic than that ordinarily found in II*, IIA, or IA granites, but this is not always, and perhaps not even commonly, the case. The subject requires much further study.

Although names are suggested above for three of the five classes and an opening is left for someone to suggest names for the other two, I should like to stress in closing that no names are actually required. They are suggested only as a convenience, since insistence

on a purely symbolic method of reference will sometimes lead to clumsy or rather silly prose. If one is willing to tolerate a little clumsiness or silliness, however, there is no need at all for class names.

In many cases, too, the symbol will convey far more information. For example, the symbol $b/mIIP_{10}$ tells at once that the rock contains less than 5 per cent muscovite, between 5 and 10 per cent biotite, more plagioclase than quartz, more quartz than alkali feldspar, and that the excess of plagioclase over alkali feldspar is less than two-fold. From the complete symbol of a class II* granite one can often set rather close limits to the mode; from the word "adamellite", even in the restricted sense here given it, one can do no such thing.

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Some Effects of Artificial Heating on Fluorite-Bearing Albite-Granite from St. Austell, Cornwall

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(PLATE II)

ABSTRACT

The granite consisted chiefly of albite, quartz, muscovite, microperthite, fluorite, and topaz ; zircon was very rare. The low to high quartz transition enhanced thermal expansion and porosity. Heating was continued step-wise to 1,300° C. and caused an irreversible increase in porosity at all temperatures investigated. The changes undergone by the various minerals, separately or through interaction, were noted. Fluorite began to melt against muscovite or alkali-feldspar between 800° and 900° C. Muscovite developed brownish pleochroism at the lower, and was replaced by mullite at the higher, temperatures. The gradual melting of feldspar, the development of cleavages and cracks in quartz, and the invasion of these cracks by feldspathic glass resembled phenomena in certain xenoliths.

The conditions that produced glass when powdered granite was heated unconfined or in a bomb are described.

INTRODUCTION

THE rock investigated was " hard purple Cornish stone ", i.e. a variety of the " chinastone " quarried in the western portion of the St. Austell granite and used as a flux by the British ceramic industry. Its petrography has been described by Keeling (1954), Richardson (1923), and earlier investigators. Hatch and Wells (1952 ; fig. 87) provided a drawing of a thin section cut from granite similar to our material but more kaolinized.

The " dry " heating of feldspars has an extensive literature, but this is not true of granites ; in particular the thermal behaviour of granites with the peculiar mineralogy of our material has received little attention. However, the minerals of " hard purple Cornish stone " were calcined individually in a matrix of kaolinite-illite clay and their behaviour noted (Weymouth and Williamson, 1953). Webb and co-workers elucidated some of the conditions which caused powdered " Cornish stone " to become vesicular on heating (Bennett *et al.*, 1941).

The material used in the present studies was obtained from ceramic suppliers. Megascopic examination and the preparation of representative thin sections showed that it was homogeneous and free from determinable xenoliths.

PETROGRAPHY OF THE GRANITE

Micrometric and chemical analyses of the granite appear in Tables

1 and 2 respectively. The rock was chiefly remarkable for its very leucocratic character, and its content of albite and of pneumatolytic minerals. It was non-porphyritic but albite, quartz, muscovite, and microperthite tended to form monomineralic groups of crystals. The resulting texture resembled that described by Hawkes (1929) as "glomero-granular" but, in contrast to what seemed implied in his original description, the crystals involved were not all anhedral; according to Hawkes (op. cit.) glomero-granular texture is well-developed in the West of England granites.

Albite, *ca.* $Ab_{97}An_3$, formed subhedral crystals often about 1 mm. long but occasionally approaching 3 mm. Zoning was imperceptible or very feebly developed.

Quartz tended to occur as small numbers of grouped anhedral crystals, individually up to 4 mm. across, with slightly undulose extinctions. It was associated with aggregates of a few microperthite

TABLE 1.—MICROMETRIC ANALYSIS OF ST. AUSTELL GRANITE; PERCENTAGES BY WEIGHT. THE 0·13 PER CENT OF OTHER MINERALS INCLUDES CASSITERITE AND OPAQUE IRON-OXIDES.

Albite . . .	39·98
Quartz . . .	33·34
Muscovite . .	14·13
Perthite . . .	7·90
Fluorite . . .	2·80
Topaz . . .	0·92
Apatite . . .	0·60
Tourmaline . .	0·13
Others . . .	0·13
Total . . .	99·93

crystals of similar dimensions. The microperthite either contained definite areas of albite, or showed a hazy extinction which suggested that exsolution had been imminent. A feldspar resembling orthoclase was contiguous to the perthite and may have been cryptoperthite. The perthite of Table 1 is both the presumed cryptoperthite and the microperthite, but albite exsolved from the latter is recorded as such.

The percentage of oxides calculated from the micrometric analysis (Table 1) were in good agreement with those determined chemically, with the exception of the alkali-oxides; the latter were Na_2O 5·2 and K_2O 2·3 per cent as against 3·5 and 3·3 respectively found chemically (Table 2). The calculation, although not necessarily significant because of the assumptions involved, suggested that an appreciable amount of potassium occurred in the albite and/or that some potassic feldspar had been recorded as albite.

Muscovite in section was commonly elongated parallel to the cleavage-traces but otherwise irregularly bounded. It was a host for

fluorite, tourmaline, apatite, and cassiterite, although these were not confined to it.

Fluorite, often purplish in bands or patches, was commonly associated with muscovite. It was frequent as irregular areas in the mica or as crystals moulded on or enclosing this mineral. The areas of fluorite were usually elongated parallel to but did not distort the cleavage-traces of the muscovite. Their arrangement resembled that of the rhombohedral carbonate in the biotite of certain lamprophyres, e.g. the lamprophyre of La Plaine in Jersey (Smith, 1933).

TABLE 2.—CHEMICAL ANALYSES OF ST. AUSTELL GRANITE.

	1.	A.
SiO_2	73·14	72·22
Al_2O_3	16·57	15·29
Fe_2O_3	*0·14	0·00
FeO	—	0·13
MgO	0·26	0·21
CaO	2·23	1·81
Na_2O	3·52	4·26
K_2O	3·32	4·17
H_2O+	0·90	0·75
H_2O-	—	0·10
CO_2	0·00	0·00
TiO_2	0·08	0·05
P_2O_5	0·53	0·47
S	0·00	0·00
MnO	0·01	Tr
F	0·97	0·63
Cl	0·00	0·02
ZrO_2	n.d.	0·00
SrO	n.d.	0·00
BaO	n.d.	0·00
Li_2O	n.d.	Tr
	101·67	100·11
Less O for F	0·41	0·26
	101·26	99·85

* State of oxidation not determined.

1. Material of present investigation dried at 105° C. Analyst Miss B. C. Terrell.

A. "China Stone." Analyst H. F. Harwood. Brammall and Harwood (1932) analysis No. 80. There is a close resemblance to analysis No. 1.

Topaz formed anhedral crystals up to *ca.* 0·5 mm. across which were sometimes surrounded by a sericite-like shell. Very rare aggregates of a similar micaceous material, unassociated with topaz in the plane of section, may have developed from cordierite. There were no minerals that obviously suggested contamination by pelitic rocks, although the possibility remained that assimilated alumina had contributed, for instance, to the formation of topaz and tourmaline (cf. Williamson, 1935, fig. 3*b*, where tourmaline is shown enclosing relics of kyanite).

Separation of the " heavy " minerals yielded abundant fluorite and topaz, with some tourmaline and cassiterite, but zircon was not encountered. Two small crystals within quartz, noted in a thin section, were the only record of the latter mineral.

Petrogenesis

It was difficult to decide what minerals, if any, were primary. The flakes of white mica which surrounded certain feldspar-crystals, or filled channels traversing them, were obviously secondary in the sense that they were of later formation than the fabric of the encompassing rock. At least some of this white mica was not obviously different from the larger crystals of muscovite. The primary status of the latter was thus not clearly established and was made more doubtful by the frequent association of these crystals with fluorite, presumably a secondary mineral.

Fluorite, topaz, tourmaline, and cassiterite are usually regarded as minerals that form late in the cooling-history of an igneous rock, either by replacement of pre-existent minerals or, possibly, by direct precipitation from a volatile-rich magma.

Albite seemed to be primary and it was so regarded, for instance, by Hall (1914). Williams (1934), however, thought that the St. Austell granite had been albitized.

Williams (op. cit.) listed analyses which showed that greisens and related rocks were deficient in ZrO_2 (cf. Table 2, Analysis A). This agreed with data given for the Skiddaw granite by Hitchen (1934) who commented specifically upon the instability of zircon under the conditions that produce greisens. Gregory (1928 ; p. 171) noted the absence of zircon from pneumatolyzed Cornish granite. The extreme rarity of zircon in the present greisen-like rock thus accords with the experience of other petrologists.

A more detailed consideration of the petrogenesis of our material would require adequate field-evidence, particularly in regard to how this material is related to other rock-types in and around the granite-mass.

The Effects of Heating on Volume and Porosity

When the granite was heated to 900° C. in a dilatometer its rate of expansion accelerated markedly at temperatures near that of the low to high quartz transition (cf. Day, Sosman, and Hostetter, 1914 ; Dale and Francis, 1943, figs. 10*a* and *b*).

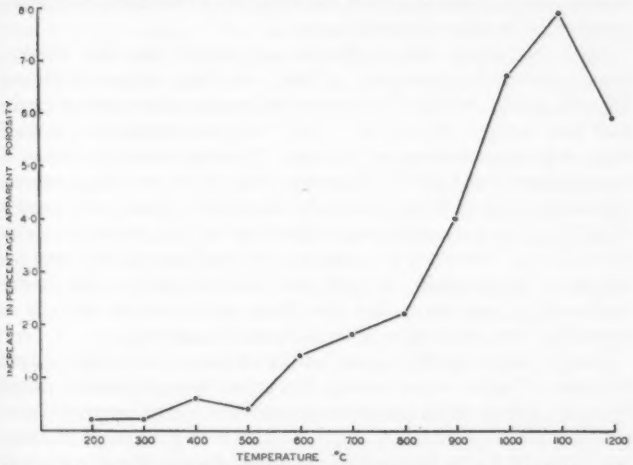
The porosities of thirteen test-pieces, found by soaking in kerosene under vacuum, ranged from 0·7 to 1·2, with an average of 0·9 per cent. The porosities of individual test-pieces were then measured before and after heating at selected temperatures ; the increases in

porosity so determined are plotted in Text-fig. 1. The sudden increase between 500 and 600° C. is ascribed to the low to high quartz transition. The test-piece heated at 1,200° C. was well-vitrified and contained bubbles, i.e. sealed pores ignored in the porosity determinations.

The Petrography of Heated Test-pieces

Introduction.

Prismatic test-pieces *ca.* 1 × ½ × ½ ins. were heated for nine hours at 400, 500, 600, 700, 800, 900, 1,000, 1,050 and 1,100° C., and for two hours at 1,100, 1,150, 1,200, 1,250 and 1,300° C. The test-piece heated at 1,300° C. was too friable to give a good thin-section and only its "heavy" minerals were studied. The other test-pieces provided both thin-sections and crops of "heavy" minerals separated in bromoform.



Text-fig. 1.—Increases in percentage apparent porosity caused by heating granite at various temperatures for one hour.

Heating was performed in electric furnaces in which the atmosphere was oxidizing. No attempt was made to attain equilibrium and the resulting metastability persisted to room-temperature where it was made evident, for instance, by the presence of glass.

The microscopically obvious thermal changes in the more abundant minerals will be described and, in general, minerals that underwent such changes at the lower temperatures will be mentioned first.

Thermal Changes in Individual Minerals.

Fluorite.—Calcium fluoride melts at 1,418° C. (Bååk, 1954) or freezes

at 1,414 ± 5° C. (McCreary, 1955). Thus, in the absence of sufficient interaction with adjacent minerals, fluorite should persist at the highest temperature of the present experiments. It was, in fact, a constant constituent of " heavy " mineral crops, even of those separated from granite calcined at 1,300° C. Thin sections, however, showed that fluorite had begun to melt against calcined mica, microperthite or albite at 900° C ; it was not commonly in contact with albite (Plate II, fig. 1). A preliminary study of the system albite-fluorite, where synthetic minerals were used, revealed no interaction between the two phases at temperatures below 1,100° C. ; the lack of interaction, which contrasted with the behaviour of the naturally occurring minerals, may have depended on the greater purity of the reactants.

The partial liquefaction of fluorite was the earliest melting-phenomenon exhibited by the granite and resulted in residual fluorite-grains surrounded by rims of greenish glass.

Melts containing calcium fluoride are notable for their fluidity; physico-chemical explanations of this have been offered (Bååk and Ölander, 1955). Marked fluidity was indicated by the tendency for the melt that bordered fluorite to " soak " into the surrounding calcined mica or to migrate along its cleavages. This was especially obvious in material heated at 1,000° C. However, some of the melt had remained around the residual fluorite where it solidified as a glass. After heating at 1,150° C. the melt usually crystallized against the calcined mica with which it was commonly in contact ; the resulting crystals were too minute to be identified. At 1,200 and 1,250° C. much of the fluorite had vanished into the molten glass from which new phases were to crystallize later on the sites of mica-crystals (see below).

Fluorite heated at 400° C. had lost its purplish colour which did not reappear at higher temperatures. The colour was presumably caused by lattice-defects which became more mobile at higher temperatures so that it could be discharged. That the colour might arise in this way was suggested by the occurrence in unheated fluorite of a purplish halo around a crystal of monazite (?).

Quartz.—Quartz in the unheated granite sometimes exhibited two cleavages (cf. Richardson, 1923) but quartz showing cleavage was much more abundant in test-pieces heated at 400 or 500° C. The cleavages were especially obvious at the edges of the thin sections, i.e. their development had been assisted by the strains set up during section-making. At 600° C. and other temperatures above that of the low to high quartz transition, the cleavages were either ill-defined or, more commonly, not visible. This was not ascribed to a healing-effect of the type mentioned by Hedvall and Carlander (1952) but to the fact that so many inter and intracrystalline cracks had formed that the stresses arising during section-making served merely to enlarge them.

These cracks were invaded by feldspathic glass at the higher temperatures. The invasion was first obvious in a test-piece heated at 1,100° C. for nine hours. It was sufficiently pronounced at 1,200° C. for fragments of quartz to have floated away from the parent crystals. There was, however, little evidence of the solution of quartz in the glass and the mineral was still persistent at 1,250° C. No tridymite or cristobalite developed (Plate II ; fig. 2).

Muscovite.—The mineral showed extremely pale streaks and patches of brown after heating at 700° C. ; at 800° C. some sections parallel to the c-axis were faintly brown, with a slightly greater absorption parallel to the original cleavage-traces. At 900° C. the colour of such sections had become a pronounced orange-brown for absorption parallel to the cleavage-traces and a very pale brown for absorption perpendicular thereto. A similar pleochroism persisted at 1,050° C. but it was now very apparent that the colour was sporadically developed. Coloured and colourless areas could appear even in the same crystal where they were irregularly but rather sharply demarcated. This may imply a lack of homogenity in the composition of the original crystals caused, e.g. by zonal growth.

The birefringence fell with increasing temperature, especially over 900° C. The colours ultimately seen were first order greys ; these were general at 1,100° C. However, some degree of birefringence was retained, even at 1,250° C., while the positive elongation parallel to the original cleavage-traces was still apparent.

Certain " basal " sections of calcined mica revealed prisms arranged like sagenite webs. Weymouth and Williamson (1953) suggested that these were mullite-prisms which had grown preferentially parallel to the basal pinacoids of the former muscovite-crystals ; this was confirmed by Sundius and Byström (1953).

Mullite is usually positively elongated. Thus sections perpendicular to the basal pinacoids of the original mica-crystal could retain positive elongation, because mullite-prisms in or at small angles to them would make the greatest contribution to their areas. It is necessary to postulate also that muscovite retains sufficient of its original structure, at temperatures below those of mullite-formation, to remain birefringent and positively elongated. This suggestion is supported by much experimental data (refs. cited by Yoder and Eugster, 1955).

At the highest temperatures, natably 1,250° C., obvious mullite-prisms, with little tendency to a sagenite-like arrangement, appeared in certain areas originally occupied by mica-flakes. It was probable that neighbouring feldspathic glass had entered some of these areas. An unidentified mineral accompanied the mullite and appeared also at lower temperatures down to 1,100° C. ; it was found in granite heated for nine, but not for two hours at this temperature. It formed minute

twinned prisms with oblique extinctions and may have been alkali-feldspar. The appearance of potash-feldspar in calcined muscovite is possible (Schairer and Bowen, 1955 ; Yoder and Eugster, 1955) and could presumably be facilitated if, as in the present instance, the mica flakes floated in feldspathic glass ; the possible " mineralizing " action of the fluorite originally associated with the mica has also to be considered.

Feldspar.—The only " clouding " shown by the heated feldspar was caused by inclusions of sericite and clay-minerals and by the thermal decomposition-products of these. According to Poldervaart and Gilkey (1954) the clouding which may accompany thermal metamorphism depends on the exsolution of iron from the feldspar-crystal or the diffusion into this crystal of iron and other elements from its environment. Neither possibility was favoured by the short heating-periods of the present experiments.

Melting was not obvious after two hours' heating at 1,100° C. but became marked after nine hours at the same temperature ; on the contrary it was less marked after two hours at 1,150° C. The significance of time, as well as of temperature, in promoting the melting of feldspar is well-known (cf. Schairer and Bowen, 1955). The boundaries between microperthite and albite seemed to be more favourable to incipient melting than those between these feldspars and quartz. Microperthite disappeared earlier than albite but it was less abundant than the latter (Table 1).

Although some albite survived two hours' heating at 1,200° C., all feldspars had been replaced by glass after two hours at 1,250° C.

Bent albite-crystals appeared in the heated granite but also in this rock prior to heating. Thus the bending could not be certainly ascribed to the effects of stress developed during heating (cf. Day and Allen, 1905, plates xxiv and xxvi).

Topaz.—No colour-changes were obvious until the mineral had been heated at 1,100° C. for nine hours. A patchy coloration then appeared ; in cleavage-fragments this was a chesnut-brown, tinged with pink with $X > Y$. At 1,250° C. certain topaz-crystals had been replaced by aggregates of positively elongated prisms, presumably of mullite (cf. Bradley, Schroeder, and Keller, 1940). Not all crystals were affected in this way and topaz, apparently unchanged, occurred among the " heavy " minerals separated from granite calcined at 1,300° C.

Miscellaneous Studies of Incipient Melting

The granite was ground to pass a 200-mesh B.S. sieve. A few milligrams of the powder were heated in a platinum envelope and then quenched in water. No glass was found after heating for 12½ days at

1,004° C. or for 22 days at 1,010° C. Traces of glass appeared after 9½ days at 1,018° C. ; this glass had a refractive index of 1·512.

The lowest temperature at which the formation of glass was detected by the examination of thin sections was 900° C., i.e. glass began to form between 800 and 900° C. The glass was found at the contacts between fluorite and alkali-feldspar or calcined mica.

The granite would be expected to melt more easily after comminution because the total surface area of the crystalline species had been enlarged and an increased number of contacts made between species of differing compositions. In fact, however, the ground granite seemed to begin melting at higher temperatures than the unground. The anomaly may be resolved if the lowest melting mixtures are assumed to require the presence of fluorite. This mineral was less than 3 per cent by weight of the rock and only a fraction of this percentage formed glass at the lower temperatures ; as seen in thin section the glass was initially a mere skin on the surfaces of fluorite-grains. Relatively small amounts of such glass could be detected in sections but it is probable that larger quantities could escape observation when pulverized granite was examined.

When the dry powder was heated in a bomb at 900° C. for a week, about 5 per cent by volume of glass appeared. This yield was greater than in any of the quenching experiments. Air, and volatiles from the granite itself, would be present in the bomb and the pressure developed was probably between 20 and 30 atmospheres. In similar experiments Goranson (1932) obtained glass from granite at still lower temperatures by the deliberate enclosure of water in the bomb.

Some Analogies with Xenocrysts and Xenoliths

The more strongly heated test-pieces resembled naturally vitrified rocks, i.e. certain rocks of the sanidinite facies (Turner, 1948, p. 62). According to Harker (1950, p. 27) natural vitrification is favoured by a high initial temperature followed by rapid cooling. These were the conditions which produced the vitrified test-pieces in the experiments that did not involve the use of bombs. Harker (op. cit.) mentioned also the effectiveness of solvents from magmatic sources, notably water, in promoting vitrification. Harker's contention is supported by the relative ease with which the granite yielded glass when heated in a bomb from which volatiles could not escape (cf. Goranson, 1932).

The test-pieces were heated under " dry " conditions but themselves contained minerals that could yield volatile compounds, notably mica, fluorite, and topaz. It is not known to what extent such compounds influenced the texture and mineralogy of the heated test-pieces. There was, however, evidence that the texture at least was influenced. Thus

bubbles formed in feldspathic glass even before all the feldspar had melted ; such bubbles were believed to develop preferentially where there had been hydrous decomposition-products in the feldspar (Weymouth and Williamson, 1953). Vesicularity is common in naturally fused rocks (cf. Williamson, 1949, pp. 725–726).

Certain partially fused test-pieces contained pseudomorphs after feldspar-crystals which were grouped rectangles of the unmelted mineral ; each rectangle was separated from its neighbours by channels of glass that had developed along cleavages. Such a structure was figured by Lacroix for xenocrystal and by Day and Allen for artificially heated feldspar (Lacroix, 1893, plate ii, fig. 1, and plate iii, fig. 12; Day and Allen, 1905, plate xix, etc.). This and related structures are common in feldspar-xenocrysts and have received various descriptive names (cf. refs. in Weymouth and Williamson, 1953).

Some test-pieces contained partially melted feldspar separated by channels of feldspathic glass from neighbouring quartz-crystals that were not visibly corroded. There are comparable structures in certain xenoliths (Holmes and Harwood, 1932).

Holmes (1936) described blind lobe-shaped ducts found in quartz xenocrysts ; these ducts were filled by glass which he believed to have originated by metasomatic replacement. This inference may be correct but, in our own experience, thermally cracked quartz may show structures which, although mechanically produced, are suggestive of replacement (Plate II, fig. 2). Quartz was almost uncorroded by such glass, even at the highest temperatures investigated and was, indeed, the last of the original crystalline phases to survive. The refractoriness of quartz in xenoliths has been frequently reported, together with its tendency to develop cleavages (e.g. by Stephens, 1954) or cracks (cf. Harker, 1950, fig. 44*a*). In the present experiments the tendency to cleave or shatter was aggravated during the preparation of the thin sections. It was not possible to assess from the literature to what extent xenocrystal quartz had been affected during such preparation.

The formation of mullite from muscovite had an apparent resemblance to the " fibrolitization " of mica reported by Williams (1934) but the latter process appears to have operated in a volatile-rich environment. The experimentally produced " mullitization " would seem to be more closely related to the development of mullite or sillimanite in buchites.

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EXPLANATION OF PLATE II

FIG. 1.—Fluorite enclosed in muscovite and characteristically elongated parallel to the traces of the mica-cleavages. The fluorite has a glassy rim too narrow to be obvious in the photograph. The mica shows a characteristic brownish coloration around the fluorite but the reason for this is not known with certainty. Granite test-piece heated at 1,000° C. for 9 hours. Ordinary light (× 75).

FIG. 2.—Thermally cracked quartz invaded by feldspathic glass along lobe-shaped and other channels. Granite test-piece heated at 1,250° C. for 2 hours. Crossed nicols (×75).

ANNOUNCEMENT

SPECIAL UNIVERSITY LECTURES IN GEOLOGY, UNIVERSITY OF LONDON

A course of three lectures on *Modern Micropalaeontology* will be given by Professor J. CUVILLIER (Professor of Structural and Applied Geology in the University of Paris) at University College, Gower Street, London, W.C. 1, on 11th, 12th, and 14th March, 1957, at 5.30 p.m. The Chair at the first lecture will be taken by MAURICE BLACK, M.A., Fellow of Trinity College, Cambridge. Admission free, without ticket.

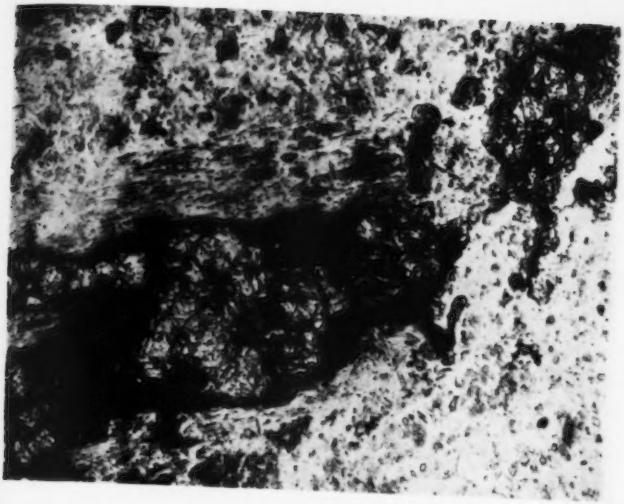


FIG. 1.

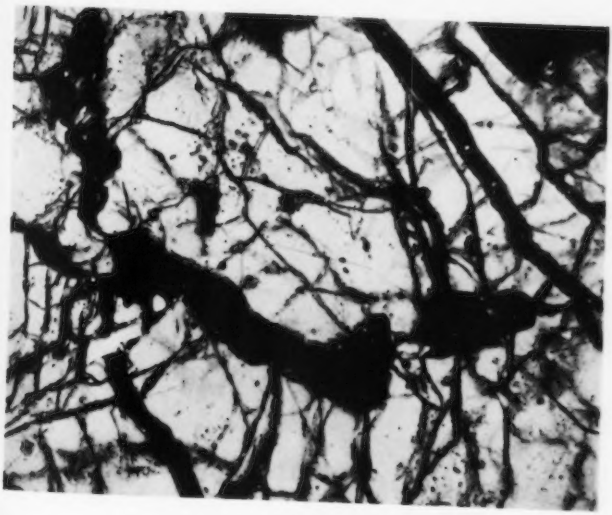


FIG. 2.

ARTIFICIAL HEATING OF GRANITE.

The Miocene of Western India

By

S. R. N. Rao, B. S. Tewari, Krishna Mohan, and A. K. Chatterji

Abstract

Miocene foraminifera from the Surat-Broach and Kathiawar regions of Western India are recorded. The suggested correlation of Miocene beds of Western India, and the stratigraphical distribution of foraminifera common to W. India, Ceylon, Indonesia, and the Middle East is indicated in 2 Tables.

THE correlation of the marine Tertiaries is now primarily based on the distribution of larger Foraminifera which, on account of their short vertical ranges and world-wide distribution, have provided important key fossils for the recognition of Tertiary stages. In India the sub-divisions of the Gaj (Miocene) are largely based on the distribution of the several species of *Ostrea*, and this has been proved to be unsatisfactory.

The type locality of the Gaj formation is the Gaj river section in Sind, Pakistan. Vredenburg (1906, 1921) classified the Gaj as follows:—

Upper Gaj with *Ostrea latimarginata*—Burdigalian (equivalent of Njalindung series of Java).

Lower Gaj with *Ostrea angulata*—Aquitanian (equivalent of Rembang series of Java).

The species of *Ostrea* recognized by Vredenburg as characteristic fossils of the two sub-divisions are known to have much longer range than recognized by him and are therefore considered to be unreliable in recognizing the different stages of Miocene.

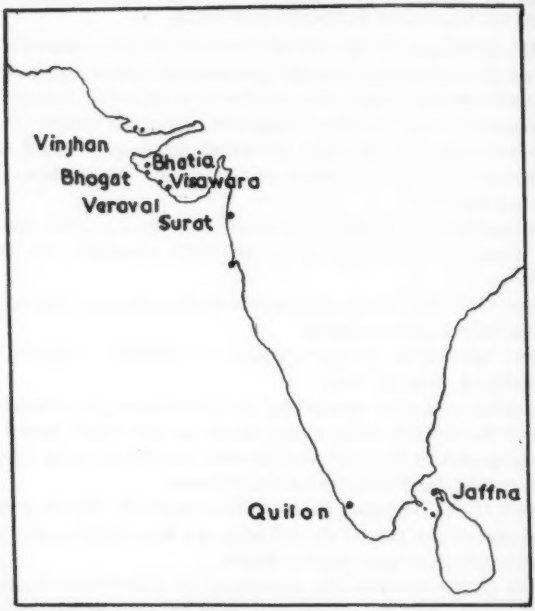
Nuttall (1926) described *Lepidocyclina blandfordi* Nuttall from this section and no sub-generic identification has been made as the species is known only from microspheric forms.

Eames (1950) recorded the occurrence of *Taberina* (= *Orbiculina*) *malabarica* (Carter) in collections made by the geologists of the Burmah Oil Co., Ltd., from the Gaj series of the Gaj river section. After a detailed review of the molluscan fauna of the Miocene of Ceylon, Quilon, Karikal, Cuddalore, and Kathiawar he states (*op. cit.*, p. 236): "The Quilon fauna has been regarded as of Vindobonian age, not on account of any similarity with known Vindobonian faunas elsewhere, but arbitrarily on account of the presence of *Archaias malabaricus* [1] in quantity at Quilon and Ceylon. The most significant evidence, however, is that *Archaias malabaricus* was found fairly commonly in collections made by geologists of the Burmah Oil Co., from the Gaj series of the Gaj river section which is the type for the Gaj series. Taking the evidence as a whole, these Ceylon, Quilon,

[1] Henson (1950) revised this to *Taberina malabarica* (Carter).

and Kathiawar faunas all seem to be of the same age, probably Upper Gaj—i.e. upper part of Lower Miocene, and the beds in which they were found were probably all formed during the same Lower Miocene transgression as were the marine Gaj deposits of Sind and Cutch." He concluded that no middle Miocene beds exist in India.

The Miocene Foraminifera occurring in the Surat–Broach region, Kathiawar and Cutch, have been investigated by several workers in



TEXT-FIG. 1.—Map of Western India and Ceylon showing Miocene beds.

this University. A summary of the stratigraphical results obtained is presented in this paper.

SURAT–BROACH

Lepidocyclina and *Miogypsina* were first recorded from the Agate-conglomerates of this region by S. R. N. Rao (1939, 1941) who considered them to be Burdigalian in age. The Agate-conglomerates overlap the *Pellatispira* limestones of Upper Eocene age (Rao, 1941; Eames, 1953) and lie directly on the Deccan Traps. The fauna recorded by Rao and Sukhbir Singh (1954) from the Agate-conglomerates is as follows:—

Lepidocyclina (*Nephrolepidina*) *sumatrensis* var. *taptiensis* (Rao and Singh), *L.* (*N.*) *tournoueri* (Lem. & Douv.), *Miogypsina irregularis* (Mich.), *M.* cf. *thecidaeformis* and *Austrotrillina howchini* (Schlumb.).

Kathiawar

After mapping the area and from a detailed study of the foraminiferal assemblage of the Miocene beds of Kathiawar, Mohan (1954) and Chatterji (April, 1955) have come to the conclusion that three distinct Miocene horizons are present here as follows (in descending order):—

3. "*Orbiculina*"—limestones of Bhogat and Verawal, containing *Austrotrillina howchini* (Schlumb.). *Taberina* (= *Orbiculina*) *malabarica* (Carter), *Lepidocyclina* (*Nephrolepidina*) *borneensis* (Provale), *L.* (*N.*) *morgani* (Lem. & Douv.), *L.* (*N.*) *martini*, var. nov., *L.* (*Trybliolepidina*) spp. nov., Miogypsina (*Miogypsina*) *irregularis* (Mich.), *M.* (*M.*) sp. nov., and *M.* (*Lepidosemicyclina*) *polymorpha* (Rutten).
2. Visawara-limestones containing *Austrotrillina howchini* (Schlumb.), *Lepidocyclina* (*Nephrolepidina*) *borneensis* (Provale), *Miogypsina* (*Miogypsina*) *irregularis* (Mich.) and *M.* (*Lepidosemicyclina*) *thecidaeformis* Rutten; and the Agate-conglomerates of Bhavanagar (in Kathiawar) containing *Miogypsina* cf. *antillea*.
1. Bhatia-limestones (*Miogypsina* beds) containing *Miogypsina* (*Miogypsina*) *irregularis* (Mich.), and *M.* (*M.*) sp. nov.

The above Foraminifera suggest a Burdigalian age for these beds.

Kutch

Tewari (1952) recorded *Taberina* (= *Orbiculina*) *malabarica* (Carter) from the Tertiary Beds of Vinjhan-Miani area, south-western Kutch, India. Mohan and Tewari who have investigated the foraminiferal fauna have provisionally recognized the following sequence in Kutch in descending order:—

4. Shales with molluscs.
3. "*Orbiculina*" shales, containing *Taberina* (= *Orbiculina*) *malabarica*, *Miogypsina* (*Lepidosemicyclina*) sp. nov., *Miolepidocyclina* sp. and *Austrotrillina howichini*.
2. Naliya *limestones*, containing *Nephrolepidina tournoueri*, *N. sumatrensis*, *Lepidocyclina* sp., *Miogypsina* sp., *Austrotrillina howchini*. } Burdigalian
1. *Miogypsina* beds, containing *Miogypsinoides* sp. and *Miogypsina* sp. } Aquitanian (?)

Conclusions

The suggested correlation of the Miocene beds of Western India and Ceylon is shown in Table I, while Table II shows the distribution of Foraminifera common to Western India, Ceylon, Indonesia, and Middle East.

TABLE I

CORRELATION OF THE MIOCENE BEDS OF WESTERN INDIA & CEYLON

AGE	JAFFNA (CEYLON)	QUILON	SURAT-BROACH	KATHIAWAR	KUTCH
BURDIGALIAN	Jaffna limestones	Quilon limestones	Agate-conglomerates	*Orbiculina* limestones Visavara limestones Bhatia limestones	*Orbulina* shales Naliya beds
AQUITANIAN (?)					*Miogypsina* beds

Taberina (= *Orbiculina*) *malabarica* (Carter) bearing beds are considered to be Burdigalian in age. In Western India the species is associated with *Trybliolepidina.*

TABLE II

DISTRIBUTION OF FORAMINIFERA COMMON TO WESTERN INDIA, CEYLON, INDONESIA & MIDDLE EAST.

INDONESIA		Eocene	Oligocene		Aquitanian	lower Miocene Burdigalian	Middle Miocene
		a / b	c	d	e(1-4) e5	f_1 - f_2	f_2 - f_3
Austrotrilina howchini *Nephrolepidina* *Trybliolepidina* *Miogypsina s.s.* *Lepidosemicyclina thecideaformis* *L. bifida* *Miogypsinoides*							
WESTERN INDIA AND CEYLON	KUTCH				*Miogypsina* beds	Naliya Lst. *Orbiculina* Shales	
	KATHIAWAR					Visavara Lst. *Orbiculina* Lst. Bhatia Lst.	
	SURAT-BROACH					Agate-conglomerates	
	QUILON					Quilon Lst.	
	JAFFNA					Jaffna Lst.	
MIDDLE EAST	SYRIA	Dj. Abiad, Dj. Bicheri & Kalaat Jaaber				Dj. Abiad, Dj. Bichri	
	PALESTINE				Ramleh Koubeibeh		
	TURKEY					Aintab	
	PERSIA	Asmari Limestones					Fars Series

Beds 1 and 2 of Kathiawar and the equivalent beds of Western India are characterized by the presence of small *Nephrolepidina* of the

sumatrensis-type, and the absence of *Eulepidina* and *Trybliolepidina*. The species of *Miogypsina* present are: *M. irregularis*, *M.* sp. nov., and *M.* (*Lepidosemicyclina*) *thecidaeformis*.

Austrotrillina howchini and *Lepidosemicyclina* occur throughout the Burdigalian. Glaessner (1951, p. 281), who has discussed the age of *Austrotrillina howchini* in the Indo-Pacific region, states: "This fossil is widely distributed but has not been found anywhere above the lower Miocene. There seems to be no reason at all to assume a younger age for these beds containing it." Möhler (1949) considered the uppermost portion of stage "e" (substage e 5) as the lower part of the Burdigalian on account of the presence of *Flosculinella reicheli* Möhler. Glaessner (1953), however, discarded the idea of bringing down Burdigalian to e 5 sub-stage as suggested by Möhler. He considers that the lowest recognizable division of the f-stage is probably Burdigalian.

The Miocene fauna as a whole shows affinity with that of Indonesia.

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REVIEW

STRUCTURAL GEOLOGY. By L. U. DE SITTER. 552 pp. with 309 text-figs. McGraw Hill, London, 1956. Price 67*s.* 6*d.*

This is an entirely new work in both conception and content. It is intended for the trained geologist rather than the first year student and there is no doubt that this gives the book at the outset an advantage with advanced students as well. Avoiding tedious elementary definitions and the usual linguistic and geometrical discussion which seems so sterile to the student, de Sitter gives his work a live positive content. The conception is ambitious and progresses in scale from the laboratory investigation of rocks and their deformation through the systematic study of field structures, to the consideration of fundamental concepts and their illustration in regional tectonic examples, concluding in a discussion of geotectonic theories and the author's own synthesis. This sequence of ideas is a natural one (indeed an almost identical development has been used in at least one university course in Britain), and the treatment which is essentially empirical succeeds in holding the interest by examples chosen, without straining the material unduly to fit pre-selected normative categories.

The 33 chapters are satisfactorily grouped into three parts. Part I *Theoretical Structural Geology* outlines stress and strain relations as developed in laboratory experiment and as applied to the deformation of rocks as seen on a small scale, and the physical principles outlined in Chapters 2 and 3 were until recently [1] only available in scattered papers or non-geological treatises. There is a useful section here on the mechanical properties of unconsolidated sediments. Model theory and tectonic experiments are placed in perspective, but later in the work much geophysical discussion seems hardly to have been written with the same understanding.

The remainder of Part I concerns the less quantitative aspects of rock deformation. In Chapter 6, on rock fracture and distortion, mylonitization should hardly be applied to all tectonic shattering of rocks (p. 85) ; boudinage is properly assessed as characteristic of strongly compressed areas; but the author's analysis of these structures as well as his diagrams have lost something in the process of retailing. At this point it may be remarked that the

[1] J. C. Jaeger, 1956, Elasticity, Fracture and Flow. Methuen.

term " tension " as used throughout the book could usually be better translated " extension " or " relative tension " and on p. 90 by " compression ". The discussions of cleavage and ptygmatic structures are admirably empirical but fall short of better explanations which seem to be well within the author's grasp. The brief survey of structural petrology gives an impression of hasty compilation.

Part II (Chapters 8 to 23) is really a systematic rather than a *Comparative Structural Geology*, and is the best part of the book. A tectonician's judgment depends largely on the breadth of his experience of the variety of structure as seen both in the field and in the literature. De Sitter has much to draw on here, and has given us an admirable selection of illustrations—including many " factual " (i.e. scale) sections. The reviewer welcomes the stress orientation treatment which shows better the genetic connection between different structures such as joints, faults, and folds, and takes into account the effect of depth on this orientation. Thrust faulting is taken along with folding (Chapter 17), with diapyric and collapse structures, domes, and cauldrons (Chapter 18), gravitational gliding tectonics (Chapter 19), and contorted beds (Chapter 21). All these are well-known themes, but it is the first time they have been given their proper emphasis in a systematic treatment.

In detail one might question whether it is usual or even proper to regard joints simply as small faults—their stress regime may be the same, but their constraints are different ; normal faults are not strictly synonymous with gravity faults, with tension faults, or dip-slip faults ; chevron folds have not usually been taken as implying *Gleitbretter* shearing in alternate limbs.

In general the author lays valuable emphasis on the implications of concentric folding in relation to cleavage- and flow-folding; the former as Busk (not mentioned) showed, has a lower limit, and this leads to a general tectonic transition or even *decollement* at depth. It also leads to diapyric and box-folded structures. But the argument (e.g. pp. 473–5) that concentric folding is characteristic of more recent orogenies, and similar folding of earlier ones, seems to carry this distinction too far.

Sedimentologically the author perhaps exaggerates the importance or originality of recent work on syn-orogenic or greywacke facies. His urging the use of Flysch and Molasse facies phases of sedimentation, with all their peculiar local associations, seems destined for a semi-mystical view of sedimentation in relation to tectonics. Similarly the author takes a big step backwards to Dana by redefining geosynclines essentially as " accumulations of sediments of great thickness which have been severely folded ". While rejecting Kay's excessive classification of geosynclines the author unfortunately uses Kay's own *exogeosyncline* twice when the sense requires (Stille's) *eugeosyncline*. He proposes three further groupings " intercontinental ", " circum-continental ", and " circumpacific " geosynclines. These tend to introduce a subjective element which the author rightly condemns in others.

Similar considerations as these mark the transition to Part III (*Geotectonics*) where mixed with a comparative regional approach there is an increasing tendency to a speculative scramble as though the author sees the end approaching and is determined to include all else important.

The Alps are very largely seen through the author's own eyes, and we have a stimulating challenge to the usual picture in this useful summary of his own views. De Sitter's outline of the Pyrenees is especially valuable. In the American structures described next, the Cordilleran system would appear to be a digest of Eardley's already summarized account; the Appalachians are similarly outlined and culminate in the author's inevitable re-interpretation. This is based on a very partial reading of even the few references quoted. With more authority de Sitter sets about a re-examination of island arcs and finds, as many do, that there is little enough known structure to support the mass of speculation which has arisen from them. Ewing's section (the only one given) across the Puerto Rico trough is a useful antidote to the familiar tectogene, but the author is not content to let well alone, and continues to speculate in the same mood as the victims

of his criticism. This culminates later in a conclusion that island arcs were rare in Palaeozoic times and absent in Archaean times. There are further chapters on shields, basin structures, and blocks.

In company with others de Sitter criticizes Stille for too rigid a scheme of synchronous tectonic epochs, but a lack of feeling for stratigraphy becomes evident when he erects his own relaxed scheme of orogenies subdivided into epochs. This is misleading because in spite of its attraction as a simplified scheme it is proposed (without detailed exposition) that many of the familiar names for orogenic epochs should have a slightly different use. Roughly each tectonic epoch is made equivalent to a system—Nevadan to Jurassic, and so on. The Helvetic epoch is apparently equivalent to the Oligocene, and opens the Alpine orogeny. The latter is proceeded by the Pyrenean orogeny which here is taken simply as Eocene (and elsewhere variously as post-Lutetian and post-Eocene)

In his discussion of magmatic phases in relation to orogenic activity the author is very ready to accept a generalization which he then dogmatically applies in the interpretation of other structures. He makes much of the presence (? exposure) or absence of syn-orogenic granites in any structure.

Four geotectonic theories are discussed in Chapter 33: the contraction theory (though Jeffreys seems not to have been referred to since 1929) drifting continents, including pole wandering (taken simply as explaining the "striking similarities of the shape of the continents" and as due only to *Polflucht* and westward drift); undation and oscillation theories; and convection currents (without reference to Holmes or the ideas associated with his name). These four are taken as the main alternative theories, and are summarily dismissed, though the author himself in the final chapter recollects some aspects for his own synthesis which involves, in the early stage of the earth's evolution, convection currents causing continental drift and in its middle stage contraction due in part to polymorphic volumetric changes in the earth's interior. As the author is finally prepared to invoke paramorphic mechanisms it is a pity he did not leave room for this when earlier he dismissed the possibility of geosynclinal subsidence as due to anything but lateral compression. These last chapters do little more than fill in the author's *Weltanschauung*, for on the geotectonic scale de Sitter's sure touch deserts him.

The work as a whole is attractively printed; full use is made of well-drawn diagrams and no resources are consumed in half-tone illustrations. There is a useful list of references at the end, in which both inclusions and omissions give a fair picture of the author's prodigious grasp. The publishers are surely to blame for so many typographical errors, and a first class opportunity spoilt by hasty production could be redeemed in a second edition.

The reviewer has found *Structural Geology* most enjoyable reading—not because there has been more than enough to comment on, but because of the substantial positive gains. The work deserves to rank with the most important publications of the last decade. It is not so much a text-book as a personal statement, and in this light one can forgive the egocentric approach. It is readable because it is touching all the time on real problems, and challenges them out of the rich experience the author has behind him. This is, indeed, a *tour de force*. De Sitter covers the ground with giant strides and keen eyes. Although somewhat anxious to be an *enfant terrible*, his sure instinct for structure gives us a faithful reflection of the present outlook in tectonics and British geologists will feel at home with this new orthodoxy.

W. B. H.